FINAL

Treatability Study in Support of Monitored Natural Attenuation at Landfill 3 (Site LF-03)

F.E. Warren Air Force Base
Cheyenne, Wyoming

Prepared For

Air Force Center for Environmental Excellence
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FINAL
TREATABILITY STUDY IN SUPPORT OF MONITORED NATURAL ATTENUATION FOR GROUNDWATER AT LANDFILL 3 (SITE LF-03)

F.E. WARREN AIR FORCE BASE
CHEYENNE, WYOMING

DECEMBER 1999

Prepared for:

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EXECUTIVE SUMMARY

This report presents the results of a treatability study (TS) conducted to evaluate the use of natural attenuation for remediation of chlorinated aliphatic hydrocarbon (CAH) - contaminated groundwater at Site LF-03, F.E. Warren AFB, Wyoming. The numerical models MODFLOW and MT3D were used in conjunction with site-specific geologic, hydrologic, and laboratory analytical data to simulate the migration and biodegradation of trichloroethene (TCE) dissolved in groundwater.

It is likely that contaminants were first introduced into groundwater at this site shortly after the opening of LF-03 around 1960. Solvents, fuels, and other liquid wastes may have been spilled or dumped, or have leaked from containers in the landfill. Contaminants dissolved in leachate are assumed to have entered groundwater over relatively large areas (i.e., the landfill), through point sources due to spills or dumping, or through contact between groundwater and residual non-aqueous phase liquid (NAPL) at or below the water table.

Contaminants observed in groundwater at LF-03 at concentrations greater than US Environmental Protection Agency (USEPA) maximum contaminant levels (MCLs) include TCE and *cis*-1,2-dichloroethene (*cis*-1,2-DCE). The dissolved CAH plume appears to have migrated approximately 1,500 feet northeast from the source area at LF-03. Comparison of TCE plumes delineated in 1993 and 1999 indicate that the TCE plume is stable, although TCE concentrations have increased at several locations within the plume.

Several lines of chemical and geochemical evidence indicate that, although dissolved TCE at LF-03 is undergoing biologically facilitated reductive dehalogenation, the occurrence of this process is limited and localized. Near the source area, the occurrence of reductive dehalogenation is most clearly indicated by a decreasing ratio of TCE to the primary metabolite *cis*-1,2-DCE.

Anaerobic conditions in the source area may be driven by low concentrations of anthropogenic fuel hydrocarbons or organic carbon from landfill leachate. Downgradient from the source area, reductive dehalogenation ceases, and *cis*-1,2-DCE produced in the source area likely is aerobically degraded. Vinyl chloride (VC) was not detected, indicating no reductive dehalogenation of *cis*-1,2-DCE downgradient from the source area. c*is*-1,2-DCE persists with TCE to the leading edge of the shallow groundwater plume. The rate of total CAH biodegradation estimated from data collected for this demonstration is approximately 6.96E-05 per day (day^{-1}), or a half-life of approximately 27 years).

Site-specific hydrogeologic and laboratory analytical data were used in the numerical groundwater model to simulate the effects of advection, dispersion, sorption, and biodegradation on the fate and transport of the TCE plume. TCE is used as an indicator compound in this report due to its relatively high concentration, low MCL, and persistence downgradient from the source area. The calibrated flow and transport for TCE was used to predict plume behavior under two remedial alternatives.

Remedial Alternative 1 incorporates monitored natural attenuation (MNA), but does not include engineered remediation or source reduction. The model used to simulate this alternative incorporates the assumption that dissolution from leachate or residual NAPL in the source area into groundwater will naturally decrease at a geometric rate of 7.3 percent per year during the 30-year predictive period. The results of the model indicate, over the next 30 years that TCE will migrate an additional 500 feet from the present plume toe to Crow Creek. However, concentrations of TCE discharging to Crow Creek are predicted to be less than 5 ug/L. Furthermore, maximum concentrations of TCE dissolved in groundwater are predicted to decrease to approximately 10 µg/L over the same 30-year period.

The model used to simulate remedial Alternative 2 assumes that partial source removal via application of engineered remedial technologies such as excavation would reduce TCE source mass. This model incorporates the assumption that the remediation will reduce the TCE source at a geometric rate of 50 percent per year over a 2-year period, followed by a 7.3 percent per year reduction due to natural weathering for the remainder of the 30-year model simulation. Results of this model indicate that source reduction at the assumed rates would result in only slightly more rapid reduction in dissolved TCE concentrations within the plume relative to Alternative 1. The Alternative 2 model predicts that maximum TCE concentrations would be reduced more rapidly near the source area, but not in downgradient portions of the plume. The overall plume extent would not be reduced, and TCE concentrations would continue to persist as with Alternative 1.

The model used to simulate remedial Alternative 3 is similar to the Alternative 2 model, but assumes total source removal. Total source removal could be achieved by locating and removing the entire source by excavation. The model was run with all source terms removed as of 1999 to simulate a total source removal scenario. Results are similar to Alternative 2; however, the TCE plume is further reduced near the source area. Maximum TCE concentrations would be reduced more rapidly near the source area, but not in the downgradient portions of the plume. The overall plume extent would be reduced near the source area, and TCE concentrations would continue to persist.

The contaminant source at Site LF-03 has not been well characterized. Therefore, the numerical models may not be accurately simulating the future strength and persistence of the source. For this reason, additional source characterization activities (e.g., soil gas survey on a tight grid spacing) may be useful to identify any remaining significant release areas. If source areas that could significantly contribute to the future magnitude and persistence of the dissolved CAH plume are identified, then consideration should be given to their remediation or total source removal (e.g., via excavation). The remaining residual, if any, and dissolved contamination could then be left to naturally attenuate over time.

In any case, future exposure to potential receptors at the site can be minimized by land use restrictions, because access to the Base (and hence most of the site) is controlled by Base security. The degree to which MNA will continue to control significant downgradient migration of the plume is not known with certainty, but will become more apparent as successive long-term monitoring (LTM) sampling events are performed.

To assess the effectiveness of both naturally-occurring processes and source removal at reducing contaminant mass and minimizing contaminant migration, groundwater from a minimum of 29 existing monitoring wells and 2 surface water stations are recommended to be sampled annually for 4 years to build a historical groundwater quality database for the site. Following completion of the 4-year annual LTM period, the LTM program should be reassessed, and sampling frequency may be reduced.

The LTM plan should be periodically reviewed and revised as appropriate on the basis of available groundwater quality data. For example, if sampling results demonstrate that the plume is in equilibrium (not migrating downgradient) or is receding toward the source area, then the sampling frequency and number of monitoring locations should be reduced appropriately. If the data collected at any time during the monitoring period indicate the need for additional remedial activities at the site, sampling frequency should be adjusted accordingly and alternative remedial actions should be evaluated.

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ACRONYMS AND ABBREVIATIONS

2D	two-dimensional
3D	three-dimensional
AFB	Air Force Base
AFCEE/ERT	Air Force Center for Environmental Excellence, Technology Transfer Division
ATC	Air Training Command
ASCII	American Standard Code for Information Interchange
bgs	below ground surface
BTEX	benzene, toluene, ethylbenzene, and xylenes
btoc	below top of casing
°C	degrees centigrade
$CaCO_3$	calcium carbonate
CAHs	chlorinated aliphatic hydrocarbons
CB	chlorobenzene
day^{-1}	per day
DCA	dichloroethane
DCB	dichlorobenzene
DCE	dichloroethene
DEI	Drilling Engineers, Inc.
DO	dissolved oxygen
Earthtech	Earthtech, Incorporated
Ebasco	Ebasco Services, Inc.
ES	Engineering Science, Inc.
°F	degrees Fahrenheit
FFA	Federal Facilities Agreement
ft^3	cubic feet
ft/day	feet per day
ft/ft	foot per foot
ft^3/s	cubic feet per second
ft/yr	feet per year
$\Delta G°r$	Gibbs free energy of the reaction
$[H^+]$	hydrogen ion concentration
HSA	hollow-stem auger
ID	inside diameter
IDW	investigation-derived waste
iron (II)	ferrous iron
iron (III)	ferric iron

IRP	Installation Restoration Program
K_d	soil distribution coefficient
K_{oc}	soil sorption coefficient
kg/L	kilograms per liter
LF-03	Landfill 3
L/kg	liters per kilogram
LTM	long-term monitoring
MCL	maximum contaminant level
µg/L	micrograms per liter
µs/cm	microsiemens per centimeter
mg/kg	milligrams per kilogram
mg/L	milligrams per liter
MNA	monitored natural attenuation
MOC	method of characteristics
mph	miles per hour
MTBE	methyl tertiary-butyl ether
mV	millivolts
NAD	National Horizontal Datum
NAPL	non-aqueous phase liquid
NAVD	National Vertical Datum
NGVD	National Geodetic Vertical Datum
NOAA	National Oceanic and Atmospheric Administration
NPL	National Priorities List
NRMRL	National Risk Management Research Laboratory
OH^-	hydroxyl group
ORD	Office of Research and Development
ORP	oxidation/reduction potential
OSWER	Office of Solid Waste and Emergency Response
OU	operable unit
Parsons ES	Parsons Engineering Science, Inc.
PCB	polychlorinated biphenyl
PCE	tetrachloroethane
PCE	tetrachloroethene
PID	photoionization detector
POC	point of compliance
ppmv	parts per million by volume
PVC	polyvinyl chloride
Redox	reduction-oxidation
RI	remedial investigation

RMS	root mean squared
RNA	remediation by natural attenuation
RSKSOP	Robert S. Kerr Laboratory Standard Operating Procedure
SAC	Strategic Air Command
SAP	sampling and analysis plan
SVOC	semivolatile organic compound
TCA	trichloroethane
TCB	trichlorobenzene
TCE	trichloroethene
TeCB	tetrachlorobenzene
TMB	trimethylbenzene
toc	top of casing
TOC	total organic carbon
TS	treatability study
USAF	United States Air Force
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
VC	vinyl chloride
VOC	volatile organic compound
WDEQ	Wyoming Department of Environmental Quality

SECTION 1

INTRODUCTION

This report was prepared by Parsons Engineering Science, Inc. (Parsons ES) and presents the results of a treatability study (TS) conducted to evaluate the use of monitored natural attenuation (MNA) as a remediation strategy for groundwater contaminated with chlorinated aliphatic hydrocarbons (CAHs) at the former Landfill 3 (LF-03), located at F.E. Warren Air Force Base (AFB), Cheyenne, Wyoming. MNA uses monitoring to document that natural attenuation mechanisms are remediating contaminants dissolved in groundwater and are controlling receptor exposure risks associated with contaminants in the subsurface.

Natural attenuation refers to the decrease in the concentration or mass of groundwater contaminants by natural physical, chemical, and biological processes. More recently, the term "monitored natural attenuation" (MNA) has been used to refer to the use of natural attenuation processes to aid in overall site remediation. The USEPA (1999) Office of Solid Waste and Emergency Response (OSWER) defines MNA as:

> *...the reliance on natural attenuation processes (within the context of a carefully controlled and monitored site cleanup approach) to achieve site-specific remediation objectives within a time frame that is reasonable compared to that offered by other more active methods. The "natural attenuation processes" that are at work in such a remediation approach include a variety of physical, chemical, or biological processes that, under favorable conditions, act without human intervention to reduce the mass, toxicity, mobility, volume, or concentration of contaminants in soil or groundwater. These* in-situ *processes include biodegradation; dispersion; dilution; sorption; volatilization; radioactive decay; and chemical or biological stabilization, transformation, or destruction of contaminants.*

As suggested by this definition, mechanisms for natural attenuation of CAHs include biodegradation, dispersion, dilution from recharge, sorption, volatilization, and chemical or biological stabilization, transformation, or destruction of contaminants. Of these processes, biodegradation is the predominant mechanism working to transform contaminants into innocuous byproducts. During natural biodegradation, indigenous microorganisms work to bring about a reduction in the total mass of contamination in the subsurface without the engineered addition of nutrients. Patterns and rates of natural attenuation can vary markedly from site to site depending on governing physical and chemical processes.

MNA is advantageous for the following reasons:

- Contaminants can be transformed to innocuous byproducts (e.g., carbon dioxide, ethene, or water), not just transferred to another phase or location within the environment;
- Current pump-and-treat technologies are energy-intensive and generally not effective in reducing residual contamination;
- The process is nonintrusive and allows continuing use of infrastructure during remediation;
- Engineered remedial technologies may pose a greater risk to potential receptors than MNA (e.g., contaminants may be transferred into another environmental medium during remediation activities); and
- MNA is generally less costly than conventional, engineered remedial technologies.

A potential disadvantage of MNA is that, in some cases, natural attenuation rates are too slow to make MNA a practical remedial alternative. In addition, biodegradation of highly chlorinated compounds, such as trichloroethene (TCE), can produce vinyl chloride (VC), which is more toxic than its parent compound. Under certain geochemical conditions, VC may accumulate in the environment rather than be transformed to innocuous byproducts.

The main emphasis of the work described herein was to evaluate the potential for naturally occurring degradation mechanisms to reduce dissolved CAH concentrations in groundwater to levels that are protective of human health and the environment. This study is not intended to be a contamination assessment report or a remedial action plan; rather, it is provided for the use of the Base and its prime environmental contractor(s) as information to be used for future decision making regarding this site.

1.1 SCOPE AND OBJECTIVES

Parsons ES, in conjunction with researchers of the USEPA National Risk Management Research Laboratory (NRMRL), was retained by the United States Air Force Center for Environmental Excellence, Technology Transfer Division (AFCEE/ERT), to conduct site characterization and groundwater modeling to evaluate the scientific defensibility of natural attenuation with long-term monitoring (LTM) as a remedial option for contaminated groundwater at LF-03.

The following tasks were performed to fulfill the project objectives:

- Review existing hydrogeologic and soil/groundwater quality data for the site;
- Conduct site characterization activities to more thoroughly characterize the nature and extent of groundwater contamination;
- Collect geochemical data in support of MNA;
- Develop a conceptual hydrogeologic model of the shallow saturated zone;
- Develop an understanding of the current contaminant distribution in the shallow saturated zone;

- Evaluate site-specific data to determine if naturally occurring processes of contaminant attenuation and destruction are occurring in shallow groundwater at the site;
- Design and execute a groundwater flow and contaminant fate and transport model for site hydrogeologic conditions;
- Simulate the fate and transport of CAHs (e.g., TCE and *cis*-1,2-dichloroethene [*cis*-1,2-DCE]) in groundwater under the influence of advection, dispersion, adsorption, and biodegradation using the calibrated model;
- Evaluate a range of model input parameters to determine the sensitivity of the model to those parameters and to consider several contaminant fate and transport scenarios;
- Determine if natural processes are minimizing dissolved CAH plume expansion so that groundwater quality standards can be met at a downgradient point of compliance (POC);
- Conduct a preliminary exposure pathways analysis for potential current and future receptors;
- Use modeling results to asses the effect of current or planned future remedial actions on the TCE plume; and
- Provide recommendations for a LTM plan that includes LTM and POC wells, and provide recommendations for a sampling and analysis plan (SAP).

Field work conducted under this program was oriented toward the collection of supplementary hydrogeologic and chemical data necessary to document and model the effectiveness of natural attenuation for restoration of CAH-contaminated groundwater. Site characterization activities in support of MNA included static groundwater level measurement, and groundwater sample collection and analysis from preexisting monitoring wells and from monitoring wells installed by Parsons ES during the field program.

Site-specific data were used to develop a solute fate and transport model for the site and to conduct a preliminary receptor exposure pathways analysis. The modeling effort was used to predict the future extent and concentration of the dissolved CAH plume by modeling the combined effects of advection, dispersion, sorption, and biodegradation. Results of the model were used to assess the potential for completion of exposure pathways involving groundwater, and to identify whether MNA is an appropriate and defensible remedial option for contaminated groundwater. The results will be used to provide technical support for the MNA remedial option during regulatory negotiations, as appropriate.

This TS contains nine sections, including this introduction, and seven appendices. Section 2 summarizes site characterization activities, and Section 3 summarizes the physical characteristics of the study area. Section 4 describes the nature and extent of soil and groundwater contamination, and geochemical evidence of contaminant biodegradation in groundwater at the site. Section 5 describes the fate and transport model and the design of the conceptual hydrogeologic model for the site, lists model

assumptions and input parameters, and describes sensitivity analysis results. Section 6 describes the predicted effects of potential future remedial alternatives on the TCE plume. Section 7 includes recommendations for a LTM plan for the site. Section 8 presents a summary and conclusions, and Section 9 lists the references used to develop this document. Appendix A contains pertinent figures and tables from previous reports, including the focused Remedial Investigation (RI) for Operable Unit (OU) 3: Landfill 3 and Nob Hill (Ebasco Services, Inc. [Ebasco], 1995). Appendix B contains well development and sampling records, borehole logs, well construction diagrams, and survey data. Appendix C presents groundwater analytical results for samples collected as a part of this TS. Appendix D contains cost calculations for remedial alternatives. Appendix E contains model input parameters and supporting calculations. Appendix F contains model input and output in American Standard Code for Information Interchange (ASCII) format on a diskette. Appendix G contains responses to comments on the draft TS.

1.2 BASE AND LF-03 BACKGROUND

F.E. Warren AFB is located in southeastern Wyoming (Township 14 North, Range 67 West, 6th Principal Meridian), adjacent to the city limits of Cheyenne (Figure 1.1). The Base is bordered by agricultural, residential, commercial, and rural areas. The main portion of the Base covers approximately 5,866 acres south of the North Platte River in a Midwestern prairie setting.

F.E. Warren AFB has been a military installation for approximately 130 years. Fort D.A. Russell was established by the U.S. Army at this location in 1867 to protect railroad workers from Indian attacks. In 1930, the fort was renamed for Francis E. Warren in honor of the Wyoming senator who played an important role in the development of the Post. During World War II, the installation more than doubled in size to support new missions. In 1947, the Air Force assumed control of the installation under the Air Training Command (ATC). The Strategic Air Command (SAC) assumed command in 1958.

LF-03 encompasses approximately 7 acres near the southeastern edge of the Base, approximately 300 feet north of Happy Jack Road, 300 feet southeast of the Base family housing area (Carlin Heights), and 1,100 feet northwest of the Nob Hill residential area (Figure 1.2). LF-03 was operational from the mid 1950s through the mid 1960s. All Base refuse was disposed at LF-03 during its operation. Data collected during previous investigations also suggests that refuse burning occurred at LF-03.

The maximum volume of fill at LF-03 is estimated to be 15,400,000 cubic feet (ft^3) (Engineering-Science, Inc. [ES], 1985). However, the actual volume of fill is probably significantly less. The exact depth and thickness of the landfill contents are unknown. The refuse deposited at LF-03 is expected to include refuse from Base shops.

LF-03 was first identified as a site that might pose a hazard to human health or the environment in the mid 1980s (ES, 1985). Four monitoring wells (61 through 64) were installed and sampled in the vicinity of LF-03 in 1987. Three additional monitoring wells (136, 138, and 147) were installed in 1988. An RI performed in support of the US Air

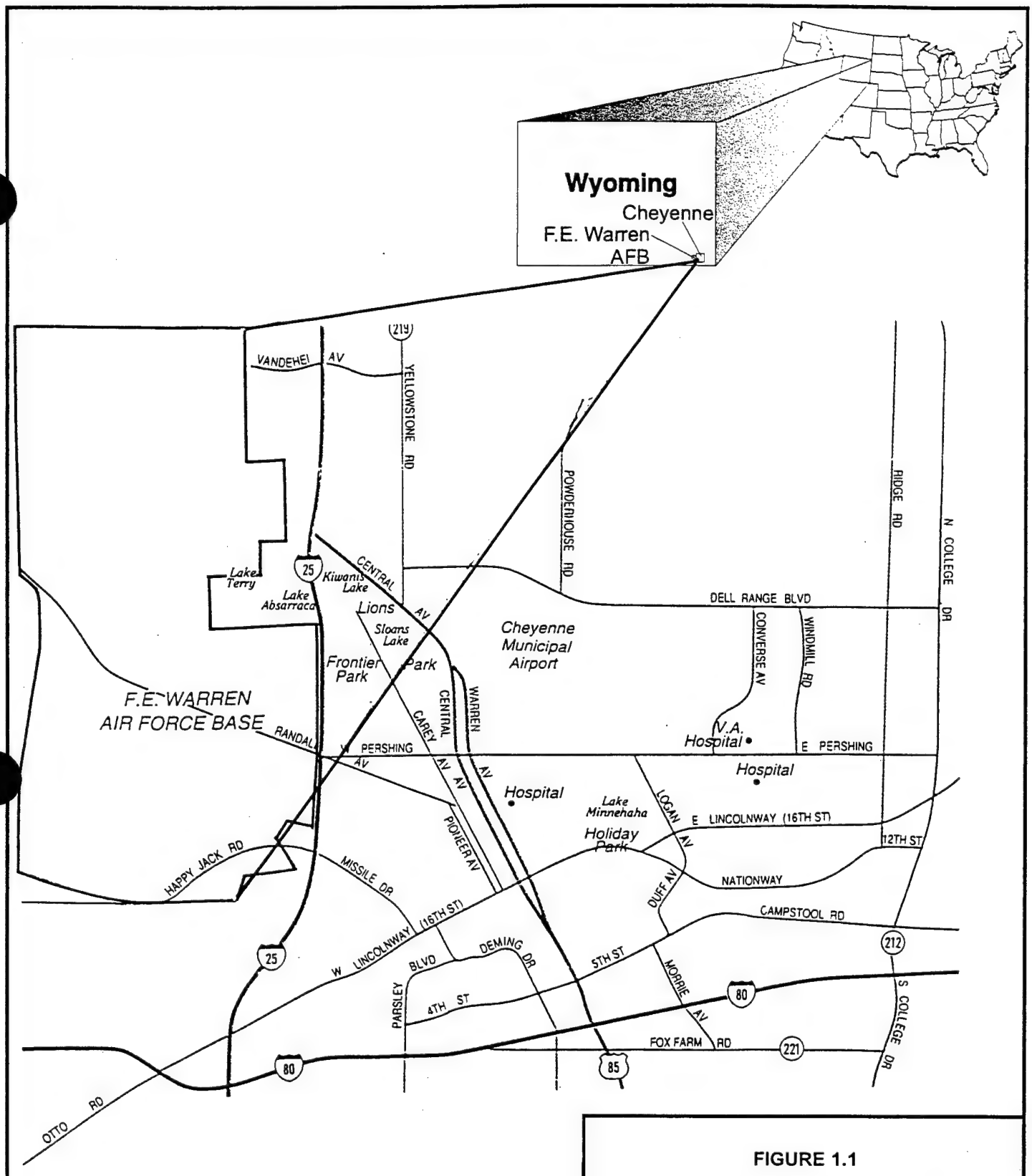


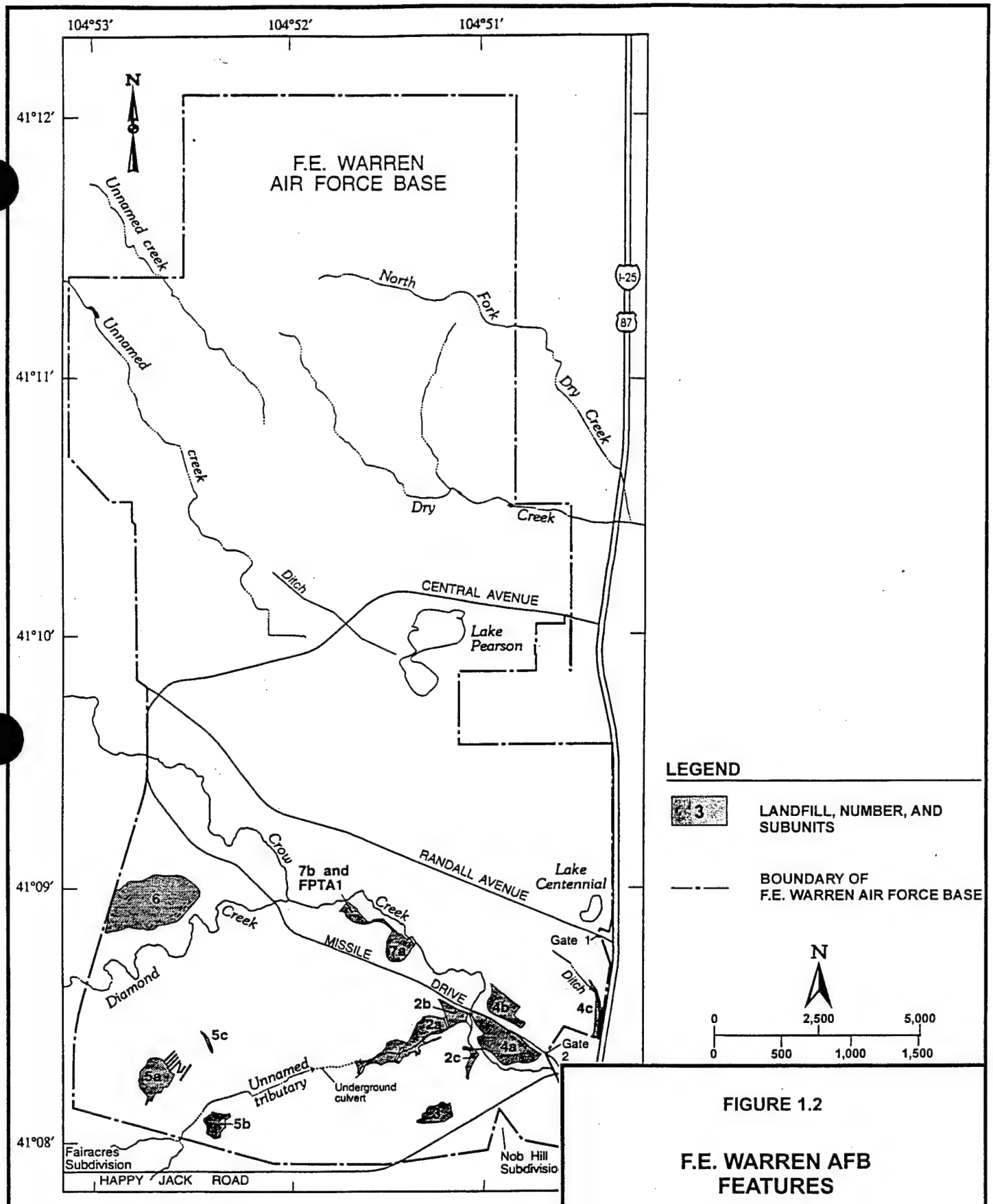
FIGURE 1.1

F.E. WARREN AIR FORCE BASE LOCATION

Site LF-03 RNA TS
F.E. Warren AFB, Wyoming

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

Source: MARCOA Publishing Inc. 1996.



Source: Ebasco, 1995.

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FIGURE 1.2

F.E. WARREN AFB FEATURES

Site LF-03 RNA TS
F.E. Warren AFB, Wyoming

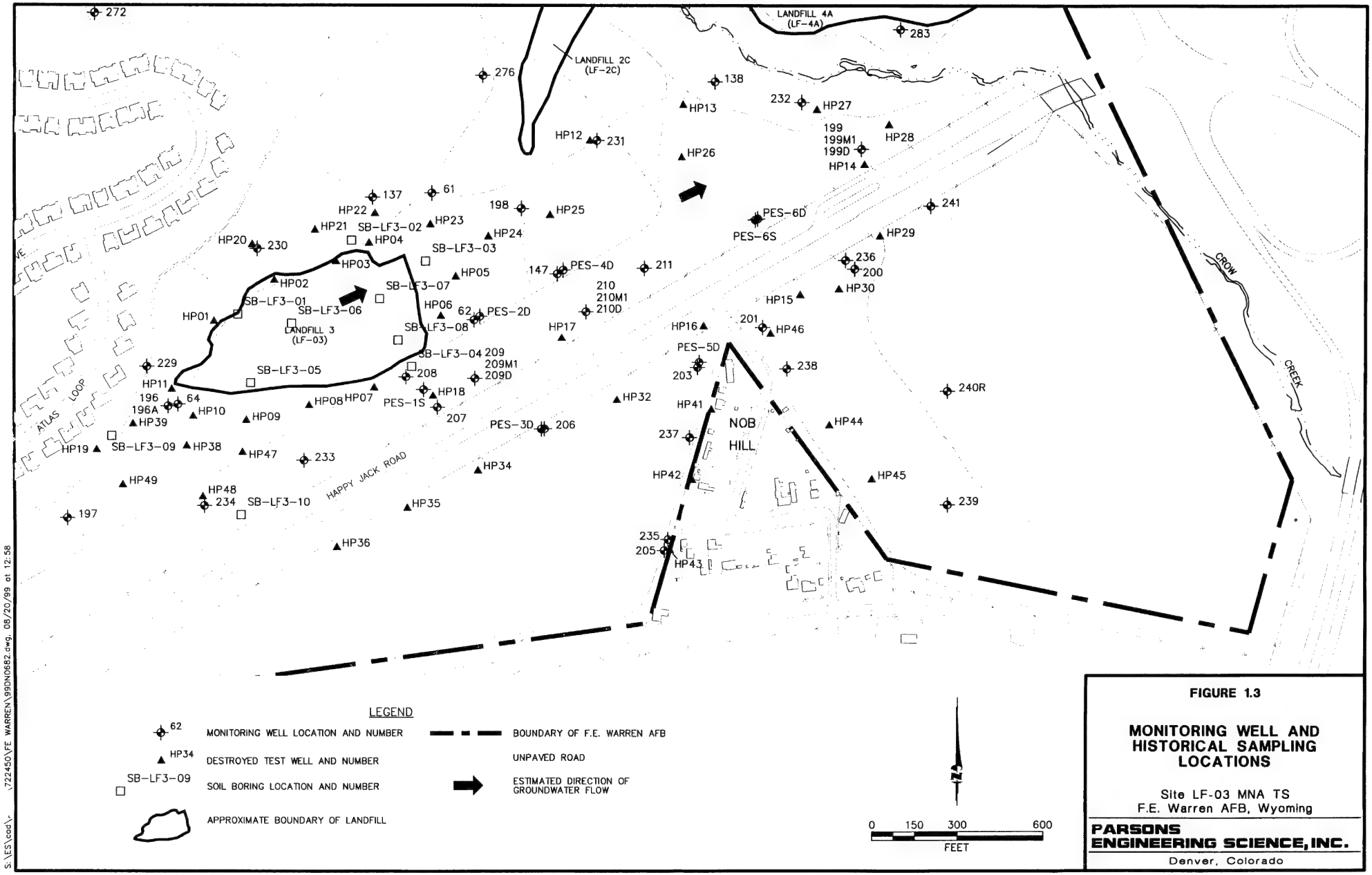
PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

Force (USAF) Installation Restoration Program (IRP) in 1991 concluded that groundwater downgradient from LF-03 was contaminated primarily by TCE, and that the source of this contamination was in or near LF-03. Fuel hydrocarbons and other chlorinated solvents also have been detected in soil and groundwater at low concentrations. The RI report also indicated that TCE-contaminated groundwater would discharge into Crow Creek (northeast of the site) without contaminating any drinking-water supply (Ebasco, 1995).

In February 1990, F.E. Warren AFB was placed on the National Priorities List (NPL). A federal facilities agreement (FFA) was signed in September 1991 by the USAF, the USEPA, and the State of Wyoming. The FFA organized the hazardous waste sites on the Base into OUs. LF-03 and Landfill 6 (LF-06) were included in OU3. In support of the RI of LF-03, 49 temporary monitoring wells and 23 permanent wells were installed in 1993, and three monitoring wells were installed in 1994 to identify the areal extent of the TCE contamination in the shallow groundwater (Ebasco, 1995). Nine additional monitoring wells were installed in 1995, under the *Modification 1 to Operable Unit 3 Work Plan* (USAF, 1994) to determine the vertical extent of contamination at LF-03. During these investigations, tetrachloroethene (PCE) and TCE also were detected in off-Base groundwater underlying the Nob Hill area. As a result of these findings, residents of the Nob Hill area were placed on the public water system.

In 1995, the USAF, USEPA, and the State of Wyoming Department of Environmental Quality (WDEQ) divided the OU3 RI into a focused RI and a comprehensive RI for LF-03 and LF-06, respectively. The focused RI for LF-03 was initiated in 1995. In August 1995, Ebasco (1995) submitted the results of the focused RI for LF-03 to F.E. Warren AFB. Ongoing remediation work at LF-03 includes FFA compliance work by Earthtech, Inc. (Earthtech).

Thirty-seven developed monitoring wells currently exist in the LF-03 area. Monitoring of these wells was performed for the 1995 focused RI; however, regular monitoring of these wells has not occurred since that time. Well locations are shown on Figure 1.3. Also presented on Figure 1.3 are temporary test well and soil boring locations sampled during previous (historical) site investigations.



LEGEND

- 62 — MONITORING WELL LOCATION AND NUMBER
- HP34 — DESTROYED TEST WELL AND NUMBER
- SB-LF3-09 — SOIL BORING LOCATION AND NUMBER
- APPROXIMATE BOUNDARY OF LANDFILL
- BOUNDARY OF F.E. WARREN AFB
- UNPAVED ROAD
- ESTIMATED DIRECTION OF GROUNDWATER FLOW

0 150 300 600
FEET

FIGURE 1.3

MONITORING WELL AND HISTORICAL SAMPLING LOCATIONS

Site LF-03 MNA TS
F.E. Warren AFB, Wyoming

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

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SECTION 2

SITE CHARACTERIZATION ACTIVITIES

This section describes the methods used by Parsons ES and USEPA NRMRL personnel to collect site-specific data at LF-03, F.E. Warren AFB, Wyoming. To meet the requirements of the MNA TS, additional data were required to evaluate near-surface geology and geochemistry, aquifer properties, and the extent of soil and groundwater contamination. Site characterization activities included use of a hollow-stem auger (HSA) drill rig for soil sample collection and groundwater monitoring well installation. Groundwater samples were collected from newly installed and existing monitoring wells. Hydraulic conductivity (slug) tests were conducted at newly installed monitoring wells. Previously collected data and data collected during this TS, were integrated to develop a conceptual hydrogeologic site model and to aid with interpretation of the site physical setting (Section 3), and to determine contaminant distribution (Section 4).

Sampling locations for the TS are shown on Figure 1.3, and a summary of activities conducted during the TS is provided by location in Table 2.1. The following subsections summarize the procedures followed during this TS. Additional details regarding investigative activities are provided in the TS work plan (Parsons ES, 1999).

Seven monitoring wells (PES-1S, PES-2D, PES-3D, PES-4D, PES-5D, PES-6S, and PES-6D) were installed by Parsons ES and Drilling Engineers, Inc. (DEI) during the field program. A summary of construction details for all site wells is presented in Table 2.2. Boring logs, well construction diagrams, and well development forms for the seven new monitoring wells are presented in Appendix B.

2.1 SOIL SAMPLE COLLECTION AND GROUNDWATER MONITORING WELL INSTALLATION

2.1.1 Pre-Drilling Activities

All subsurface utility lines or other man-made subsurface features were located, and proposed borehole locations were cleared and approved by the Base prior to drilling activities.

2.1.2 Hollow-Stem Auger Drill Rig Field Activities

The seven new monitoring wells were installed in boreholes advanced by DEI using a CME 75 HSA drill rig from April 26 through May 6, 1999. The boreholes for the proposed monitoring wells were drilled to varied depths in the shallow groundwater aquifer to evaluate vertical site conditions.

TABLE 2.1
SUMMARY OF TREATABILITY STUDY ACTIVITIES
SITE LF-03 MNA TS
F.E. WARREN AFB, WYOMING

Location	Monitoring Well Installation	Slug Test Analysis	Soil Analyses		Groundwater Analyses											
			Total Organic Carbon	TCE/ PCE[a/] Analysis	CAHs[b/]	Water Level Measurement	Fuel Hydro-carbons and Fuel Carbon	Total Organic Carbon	Well Head Analyses[c/]	Mobile Lab Analyses[d/]	Methane, ethane, and ethene	Chloride	Ammonia	Nitrate + Nitrite (as Nitrogen)	Sulfate	Carbon Dioxide
PES-1S	X[e/]	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
PES-2D	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
PES-3D	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
PES-4D	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
PES-5D	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
PES-6S	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
PES-6D	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
61						X										
62					X	X	X	X	X	X	X	X	X	X	X	X
64					X	X	X	X	X	X	X	X	X	X	X	X
137						X										
138						X										
147					X	X	X	X	X	X	X	X	X	X	X	X
196					X	X	X	X	X	X	X	X	X	X	X	X
196A					X	X	X	X	X	X	X	X	X	X	X	X
197					X	X	X	X	X	X	X	X	X	X	X	X
198					X	X	X	X	X	X	X	X	X	X	X	X
199					X	X	X	X	X	X	X	X	X	X	X	X
199M1					X	X	X	X	X	X	X	X	X	X	X	X
199D					X	X	X	X	X	X	X	X	X	X	X	X
201					X	X	X	X	X	X	X	X	X	X	X	X
203					X	X	X	X	X	X	X	X	X	X	X	X
206					X	X	X	X	X	X	X	X	X	X	X	X
207					X	X	X	X	X	X	X	X	X	X	X	X
208					X	X	X	X	X	X	X	X	X	X	X	X
209					X	X	X	X	X	X	X	X	X	X	X	X
209M1					X	X	X	X	X	X	X	X	X	X	X	X
209D					X	X	X	X	X	X	X	X	X	X	X	X
210					X	X	X	X	X	X	X	X	X	X	X	X
210M1					X	X	X	X	X	X	X	X	X	X	X	X
210D					X	X	X	X	X	X	X	X	X	X	X	X
211					X	X	X	X	X	X	X	X	X	X	X	X
229						X										
230						X										
231						X										
232					X	X	X	X	X	X	X	X	X	X	X	X
233					X	X	X	X	X	X	X	X	X	X	X	X
234						X										
235						X										
236					X	X	X	X	X	X	X	X	X	X	X	X
237					X	X	X	X	X	X	X	X	X	X	X	X
238					X	X	X	X	X	X	X	X	X	X	X	X
239						X										
240R						X										
241						X										

[a/] TCE/PCE = trichloroethene and tetrachloroethene.

[b/] CAHs = chlorinated aliphatic hydrocarbons.

[c/] Well head analytical parameters included dissolved oxygen, reduction/oxidation potential, pH, temperature, and conductivity.

[d/] Mobile laboratory analyses include total alkalinity, ferrous iron, manganese, carbon dioxide, total phenols, and hydrogen sulfide.

[e/] X indicates that the analysis was completed.

TABLE 2.2
MONITORING WELL SUMMARY AND MAY 1999 GROUNDWATER ELEVATIONS
SITE LF-03 MNA TS
F.E. WARREN AFB, WYOMING

Well/Borehole Identification	Completion Date	Borehole Diameter (inches)	Well Diameter (inches)	Depth of Well (feet bgs)[a/]	Screened Interval (feet bgs)	Land Surface Elevation (feet msl)[b/]	Stick-Up of PVC (feet ags)[c/]	Depth to Water May 10, 1999 (feet btoc)[d/]	Water Table Elevation May 10, 1999 (feet msl)[e/]
61	5/14/1987	NA[f/]	4.0	34.0	19-34	6145.4	0.4	26.11	6119.69
62	5/15/1987	NA	4.0	34.0	19-34	6137.3	0.25	18.94	6118.61
64	5/18/1987	NA	4.0	44.0	29-44	6165.2	0.25	33.44	6132.01
137	8/30/1988	NA	4.0	38.0	23-28	6149.6	1	29.04	6121.56
138	8/30/1988	NA	4.0	53.0	38-53	6111.1	1.15	21.86	6090.39
147	8/31/1988	NA	4.0	28.0	13-28	6128.6	1.75	14.65	6115.70
196	5/26/1993	8.625	2.0	94.0	84-94	6165.60	2.45	38.08	6129.97
196A	6/7/1993	8.625	2.0	56.5	46.5-56.5	6165.60	2.25	36.45	6131.40
197	9/20/1993	8.625	2.0	39.5	24.5-39.5	6174.25	2.3	39.74	6136.81
198	9/23/1993	8.625	2.0	34.5	22-34.5	6141.20	2.2	28.21	6115.19
199	9/23/1993	8.625	2.0	19.5	4.5-19.5	6085.45	2.45	12.26	6075.64
199M1	8/17/1995	8.625	2.0	44.5	34-44	6085.45	2.35	6.73	6081.07
199D	8/15/1995	8.625	2.0	71.5	61-71	6085.45	1.45	1.59	6085.31
200	9/24/1993	8.625	2.0	22.5	7.5-22.5	6107.04	1.50	17.13	6091.41
201	9/29/1993	8.625	2.0	19.5	4.5-19.5	6110.79	1.8	6.36	6106.23
203	9/28/1993	8.625	2.0	19.5	4.5-19.5	6117.11	1.5	6.85	6111.76
205	9/28/1993	8.625	2.0	19.5	9.5-19.5	6129.08	1.5	16.34	6114.24
206	9/28/1993	8.625	2.0	19.7	4.7-19.7	6124.12	1.5	8.28	6117.34
207	9/23/1993	8.625	2.0	29.4	14.4-29.4	6137.99	1.6	19.61	6119.98
208	9/20/1993	8.625	2.0	45.5	30.5-45.5	6151.79	2.55	35.45	6118.89
209	9/22/1993	8.625	2.0	23.0	13-23	6132.21	2.3	16.54	6117.97
209M1	9/1/1995	8.625	2.0	32.5	27-32	6132.21	2.05	16.24	6118.02
209D	8/30/1995	8.625	2.0	78.5	68-78	6132.21	1	14.99	6118.22
210	9/22/1993	8.625	2.0	23.0	8-23	6125.78	2.4	13.81	6114.37
210M1	8/24/1995	8.625	2.0	52.0	41.5-51.5	6125.78	2.15	14.51	6113.42

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TABLE 2.2 (Continued)
MONITORING WELL SUMMARY AND
MAY 1999 GROUNDWATER ELEVATIONS
SITE LF-03 MNA TS
F.E. WARREN AFB, WYOMING

Well/Borehole Identification	Completion Date	Borehole Diameter (inches)	Well Diameter (inches)	Depth of Well (feet bgs)[a/]	Screened Interval (feet bgs)	Land Surface Elevation (feet msl)[b/]	Stick-Up of PVC (feet ags)[c/]	Depth to Water May 10, 1999 (feet btoc)[d/]	Water Table Elevation May 10, 1999 (feet msl)[e/]
210D	8/22/1995	8.625	2.0	78.5	68-78	6125.78	2.4	17.36	6110.82
211	9/23/1993	8.625	2.0	24.3	9.3-24.3	6122.87	2.2	16.12	6108.95
229	9/30/1993	8.625	2.0	34.8	24.8-34.8	6166.41	1.85	36.95	6131.31
230	9/30/1993	8.625	2.0	42.5	27.5-42.5	6161.64	1.5	39.14	6124.00
231	9/28/1993	8.625	2.0	27.5	12.5-27.5	6124.65	1.3	21.00	6104.95
232	9/29/1993	8.625	2.0	20.0	7.5-20	6088.94	1.05	7.60	6082.39
233	9/30/1993	8.625	2.0	40.5	25.5-40.5	6157.69	2.65	33.39	6126.95
234	10/1/1993	8.625	2.0	37.5	22.5-37.5	6164.68	1	35.27	6130.41
235	10/22/1993	8.625	2.0	25.5	10.5-25.5	6129.07	1.5	15.80	6114.77
236	10/22/1993	8.625	2.0	27.5	12.5-27.5	6107.32	1.5	17.11	6091.71
237	4/21/1994	8.625	2.0	19.0	6.5-19	6116.06	1.5	5.05	6112.51
238	4/22/1994	8.625	2.0	19.0	6.5-19	6113.20	2.3	8.90	6106.60
239	9/7/1995	8.625	2.0	26.0	10.5-25.5	6119.34	2.1	14.08	6107.36
240R	9/6/1995	8.625	2.0	28.5	8-28	6105.26	1.35	8.66	6097.95
241	4/18/1995	8.625	2.0	16.0	3.5-16	6087.87	1.35	3.82	6085.40
PES-1S	4/30/1999	8.250	2.0	39.0	29-39	6146.76	1.49	28.66	6119.59
PES-2D	4/29/1999	8.250	2.0	49.5	39.5-49.5	6137.86	1.63	20.39	6119.10
PES-3D	5/4/1999	8.250	2.0	39.5	34.5-39.5	6124.86	2.05	9.34	6117.57
PES-4D	4/28/1999	8.250	2.0	49.5	44.5-49.5	6129.10	1.83	16.14	6114.79
PES-5D	5/4/1999	8.250	2.0	39.5	34.5-39.5	6117.51	1.69	7.20	6112.00
PES-6S	4/27/1999	8.250	2.0	32.0	22-32	6110.19	1.60	12.42	6099.37
PES-6D	4/26/1999	8.250	2.0	44.5	39.5-44.5	6110.10	1.71	14.19	6097.62

[a/] feet bgs = feet below ground surface.

[b/] feet msl = feet above mean sea level NGVD of 1929 (Ebasco, 1995).

[c/] feet ags = feet above ground surface.

[d/] feet btoc = feet below top of casing.

[e/] NGVD of 1929.

[f/] NA = not available.

2.1.2.1 Equipment Decontamination

Prior to arriving at the site and after each boring, draw works and augers were decontaminated with a steam-cleaning system. Water used in equipment decontamination was obtained from a potable water supply provided by DEI. Equipment decontamination was performed at a lined decontamination pad constructed on site. Spent decontamination water from the pad was collected and contained in 650-gallon collection tanks supplied by Arvada Treatment Center for later disposal as investigation-derived waste (IDW).

2.1.2.2 Soil Sample Collection and Analysis

The HSA drill rig was used to advance the borehole for each new monitoring well. Soil samples were collected using a decontaminated continuous California sampler for visual description, volatile organic compound (VOC) headspace screening, and laboratory analysis of VOCs and total organic carbon (TOC).

At each borehole location, soil samples were collected and logged continuously to the total depth of the borehole. After visual examination, soil samples from each 2.5-foot interval was placed in an unused, clean, plastic baggie for photoionization detector (PID) headspace measurements of ionizable VOCs. Baggies containing soil samples collected for the headspace screening procedure were quickly sealed and stored for at least 15 minutes at the ambient temperature. Semi-quantitative measurements were made by puncturing the bag seal with the PID probe and reading the concentration of the headspace gases. The PID relates the concentration of total VOCs in the sample to an isobutylene calibration standard. The PID also was used to monitor for VOCs in the worker breathing zone. The Parsons ES scientist maintained a descriptive log of subsurface materials recovered. Geologic borehole logs with soil sampling intervals and PID screening results are included in Appendix B.

Soil samples for laboratory analysis were collected from the capillary fringe directly above the water table. Soil samples for VOCs and TOC were collected using an Encore® sampler. Soil samples for analysis of the benzene, toluene, ethylbenzene, and xylenes (BTEX), trimethylbenzenes (TMBs), naphthalenes, tetrachloroethene (PCE) and TCE were transferred to sample containers containing a methylene chloride extraction solution. Soil samples for analysis of chlorinated ethenes were transferred to sample containers containing a xylene extraction solution. Soil samples collected for TOC analysis were placed in non-preserved sample jars. Soil samples were submitted to NRMRL in Ada, Oklahoma for analysis. Soil sample analytical methods are listed in Table 2.3.

During monitoring well installation, the excess soils generated during drilling were temporarily stored in a portable bin. Soils were then transferred to an onsite 20-cubic-yard rolloff bin after each well installation to await sampling, laboratory analysis, and disposal. After laboratory analysis, the soils were approved for disposal at the Waste Management, Inc., Weld County (Colorado) Landfill.

TABLE 2.3
ANALYTICAL PROTOCOLS FOR GROUNDWATER AND SOIL SAMPLES
SITE LF-03 MNA TS
F.E. WARREN AFB, WYOMING

MATRIX Analyte	METHOD	FIELD (F) OR ANALYTICAL LABORATORY (L)
WATER		
Ferrous Iron (Fe^{+2})	Colorimetric, Hach Method 8146 (or equivalent)	F
Sulfide	Colorimetric, Hach Method 8131 (or equivalent)	F
Alkalinity (Carbonate [CO_3^{-2}] and Bicarbonate [HCO_3^{-1}])	Titrimetric, Hach Method 8221 (or equivalent)	F
Carbon Dioxide	Titrimetric, Hach Method 1436-01 (or equivalent)	F
Reduction/Oxidation Potential	Direct-reading meter	F
Dissolved Oxygen	Direct-reading meter	F
pH	Direct-reading meter	F
Conductivity	Direct-reading meter	F
Temperature	Direct-reading meter	F
Nitrate + Nitrite (as Nitrogen)	Lachat FIA Method 10-107-04-2-A	L
Ammonia	Lachat FIA Method 10-107-06-1	L
Chloride	Waters Capillary Electrophoresis Method N-601	L
Sulfate	Waters Capillary Electrophoresis Method N-601	L
Methane, Ethane, Ethene	RSKSOP-194[a]/RSKSOP-175	L
Total Organic Carbon	RSKSOP-102	L
VOCs (CAHs, Chlorobenzenes)[b]	RSKSOP-148	L
BTEX, TMBs, and MTBE[c]	RSKSOP122	L
SOIL		
Total Organic Carbon	LECO Method 203-601-272	L
VOCs (Aromatics, CAHs)	RSKSOP-124, modified	L

[a] RSKSOP = Robert S. Kerr Laboratory standard operating procedure.

[b] VOCs = volatile organic compounds; CAHs = chlorinated aliphatic hydrocarbons.

[c] BTEX = benzene, toluene, ethylbenzenes, and xylenes; TMBs = trimethylbenzenes; MTBE = methyl tertiary-butyl ether.

2.1.2.3 Monitoring Well Installation

Using the HSA drill rig, Parsons ES and DEI staff installed seven 2-inch inside-diameter (ID) monitoring wells. Wells PES-1S, PES-2D, PES-3D, PES-4D, PES-5D, PES-6S, and PES-6D are shown on Figure 1.3.

2.1.2.3.1 Materials

Monitoring wells were constructed of flush-threaded 2-inch-ID Schedule 40 polyvinyl chloride (PVC) casing and screen. Monitoring well screens ranged from 5 to 10 feet in length and were factory-slotted with 0.010-inch openings. Each monitoring well was fitted with a vented PVC cap. Well materials were inspected for cleanliness prior to use. No glue or solvents were used with monitoring well materials.

2.1.2.3.2 Installation

Monitoring wells were installed through the drilling augers. After the monitoring well screen and riser pipe were in place, the annular backfill materials were gradually added through the augers down the borehole. Monitoring wells were completed by filling the borehole around the well casing with 20-40 graded sand, bentonite chips, and bentonite/cement grout. All monitoring wells were completed with a 2-foot stick-up and protective casing in accordance with Base well installation standards. Circular concrete pads 6 feet in diameter were constructed at the base of the monitoring wells. Monitoring well completion logs are included in Appendix B.

2.1.2.3.3 Development

Prior to sampling, newly installed monitoring wells were developed to remove sediment from inside the well casing and flush fines and cuttings from the sand pack and the portion of the formation adjacent to the well screen. Monitoring well development was accomplished using Teflon®-lined disposable bailers. The bailer was lowered to the bottom of the well and surged so that fines were agitated and removed from the well in the development water. Development continued until at least 10 casing volumes of water were removed from the monitoring well, and the temperature, pH, oxidation/reduction potential (ORP), conductivity, and dissolved oxygen (DO) concentrations of the extracted groundwater had stabilized. Monitoring well development records are included in Appendix B. All development water was contained in a 650-gallon portable tanks, and was subsequently disposed at the Arvada Treatment Center, Colorado.

2.2 GROUNDWATER SAMPLING

Groundwater sampling procedures followed those described in the site work plan (Parsons ES, 1999), and are summarized in the following sections. Groundwater sampling took place from May 3 to May 7, 1999, and consisted of collecting groundwater samples from 27 of the 37 previously installed wells at the site (62, 64, 147, 196, 196A, 197, 198, 199, 199M1, 199D, 201, 203, 206, 207, 208, 209, 209M1, 209D, 210, 210M1, 210D, 211, 232, 233, 236, 237, and 238) and from all 7 of the newly installed wells (PES-1S, PES-2D, PES-3D, PES-4D, PES-5D, PES-6S, and PES-6D). Refer to Table 2.1 for analyses conducted at each monitoring well.

2.2.1 Preparation and Equipment Cleaning

All equipment used for sampling was assembled, properly cleaned, and calibrated (if required) prior to use in the field. All portions of sampling and test equipment that contacted the sample were thoroughly cleaned before use. This equipment included the water level probe and cable and equipment for measuring onsite groundwater chemical parameters. The equipment was cleaned using the following protocol:

- Rinsed with isopropyl alcohol;
- Rinsed with distilled or deionized water; and
- Air dried prior to use.

Special care was taken to prevent cross contamination of the groundwater and extracted samples through contact with improperly cleaned equipment. In addition, a clean pair of new, disposable latex gloves was worn each time a different well was sampled. Field analytical equipment was calibrated according to the manufacturers' specifications prior to field use.

Prior to starting the sampling procedure, the area around the well was cleared of foreign materials, such as brush, rocks, and debris. These procedures prevented sampling equipment from inadvertently contacting debris around the monitoring wells. The integrity of the monitoring wells also was inspected, and any irregularities in the visible portions of the wells, protective covers, or concrete pads were noted.

2.2.2 Water Level and Total Depth Measurements

Prior to removing any water from the monitoring well, the static water level was measured. A Solinist® electrical water level probe was used to measure the depth to groundwater below the well datum to the nearest 0.01 foot. After measurement of the static water level, the water level probe was lowered to the bottom of the new wells for measurement of total depth (recorded to the nearest 0.1 foot). The saturated casing volume for each well was calculated based on these measurements, or using total depths recorded on well construction diagrams (existing wells).

2.2.3 Monitoring Well Purging

Prior to sampling, each monitoring well was purged to remove stagnant water from the well casing. Where possible, the volume of water removed from each well was at least three times the calculated saturated casing volume. Where it was not possible to remove three times the calculated casing volume (i.e., the well was purged dry), the well was allowed to recharge until sufficient water was present to obtain the necessary sample quantity. Purging continued until pH, DO, ORP, conductivity, and temperature stabilized. Depending on the depth to groundwater at respective monitoring wells, either a decontaminated Bennett® submersible pump or a MasterFlex® peristaltic pump with dedicated tubing was used for purging. All purge water from monitoring wells was collected in 5-gallon buckets and transferred to 650-gallon portable tanks for subsequent disposal at the Arvada Treatment Center in Colorado.

2.2.4 Sample Collection

Dedicated or decontaminated Bennett® or MasterFlex® pumps and tubing were used to extract groundwater samples from monitoring wells. The samples were transferred directly into the appropriate sample containers. The water was carefully poured down the inner walls of each sample bottle to minimize aeration of the sample. Sample bottles for BTEX, TMBs, methyl tertiary-butyl ether (MTBE), CAHs, methane, ethane, and ethene were filled so that there was no headspace or air bubbles within the container. Groundwater sampling records are provided in Appendix B.

A variance from the published work plan (Parsons, 1999) procedures was noted during field activities. Contrary to work plan procedures for sample collection, a base was used in the preservation of VOC samples, instead of an acid.

2.2.5 Groundwater Sample Analysis

Laboratory analyses for BTEX, TMBs, MTBE, CAHs, nitrate + nitrite (as nitrogen), ammonia, chloride, sulfate, methane, ethane, ethene, and TOC were performed at the NRMRL in Ada, Oklahoma (Table 2.3).

Because the pH, electrical conductivity, DO, ORP, and temperature of the groundwater may change significantly within a short time following sample acquisition, these parameters were measured in the field in a flow-through cell at the outlet of the purge pump. DO concentrations were recorded after the readings stabilized, and in all cases represent the lowest DO concentration observed. Other time-sensitive parameters, including ferrous iron, carbon dioxide, alkalinity, and hydrogen sulfide, were analyzed at the USEPA NRMRL onsite mobile laboratory immediately after sample collection.

2.3 SAMPLE HANDLING

The fixed-base analytical laboratory, NRMRL, provided analyte-specific pre-preserved sample containers. The sample containers were filled as described in the previous sections. The samples were labeled as described in the work plan (Parsons ES, 1999). After the samples were sealed and labeled, they were transported to the USEPA NRMRL onsite mobile laboratory. Sample shipment to NRMRL and the associated chain-of-custody documentation was the responsibility of NRMRL field personnel.

2.4 AQUIFER TESTING

Slug tests were performed at LF-03 by Parsons ES on May 5 through May 10, 1999. Falling and rising head slug tests were performed at the seven new monitoring wells (PES-1S, PES-2D, PES-3D, PES-4D, PES-5D, PES-6S, and PES-6D). Parsons ES personnel used testing procedures similar to those described in the work plan (Parsons ES, 1999). Slug test data were analyzed using the AQTESOLV® software package (Geraghty and Miller, Inc., 1994) and the methods of Bouwer and Rice (1976) and Bouwer (1989) for unconfined conditions. Slug test results are presented in Section 3.3 and Appendix B.

2.5 SURVEYING

After completion of field work, the locations and elevations of all new monitoring wells were surveyed by Steil Surveying Services, a Wyoming-licensed land surveyor from Cheyenne, Wyoming. The horizontal location of the well casings were measured relative to existing control points referenced to the National Horizontal Datum (NAD) of 1983 plane coordinate system. Horizontal locations were surveyed to the nearest 0.1 foot. The vertical elevations of the measurement datum (i.e., top of PVC well casing) and the concrete well pad (approximate ground surface) adjacent to the well casings were measured relative to existing control points referenced to the National Geodetic Vertical Datum (NGVD) of 1929 and the National Vertical Datum (NAVD) of 1988. Measurement datum and ground surface elevations were surveyed to the nearest 0.01 foot. Survey data are summarized in Table 2.4, and included in Appendix B.

TABLE 2.4
SURVEY RESULTS FOR
NEWLY INSTALLED MONITORING WELLS
SITE LF-03 MNA TS
F.E. WARREN AFB, WYOMING

Well Identification	Northing	Easting	Top of Casing Elevation (NAVD 88)[a/]	Top of Casing Elevation (NGVD 29)[b/]	Concrete Pad Elevation (NAVD 88)	Concrete Pad Elevation (NGVD 29)	Protective Casing Stick-Up
PES-1S	231,530.3	742,977.5	6,151.57	6,148.25	6,150.08	6,146.76	1.49
PES-2D	231,786.5	743,174.2	6,142.81	6,139.49	6,141.18	6,137.86	1.63
PES-3D	231,392.2	743,388.2	6,130.23	6,126.91	6,128.18	6,124.86	2.05
PES-4D	231,946.5	743,463.3	6,134.25	6,130.93	6,132.42	6,129.10	1.83
PES-5D	231,627.0	743,941.5	6,122.52	6,119.20	6,120.83	6,117.51	1.69
PES-6S	232,118.7	744,136.2	6,115.11	6,111.79	6,113.51	6,110.19	1.6
PES-6D	232,122.6	744,144.7	6,115.13	6,111.81	6,113.42	6,110.10	1.71

[a/] Top of casing elevation relative to National Vertical Datum (NAVD) of 1988.

[b/] Top of casing elevation relative to National Geodetic Vertical Datum (NGVD) of 1929.

SECTION 3

PHYSICAL CHARACTERISTICS OF THE STUDY AREA

Existing site-specific data were reviewed and supplemented with data collected by Parsons ES in May 1999 to develop a synopsis of LF-03 physical characteristics. In addition to field investigation results from this TS, data from the following sources are incorporated in this section:

- Installation Restoration Program, Phase I - Records Search, F.E. Warren AFB, Wyoming (ES, 1985);
- Remedial Investigations for F.E. Warren Air Force Base, Wyoming: Cheyenne, Wyoming, Administrative Report prepared by the United States Geologic Survey (USGS) for the USAF (USAF, 1991); and
- Focused Remedial Investigation for Operable Unit 3: Landfill 3 and Nob Hill at F.E. Warren Air Force Base, Wyoming (Ebasco, 1995).

3.1 TOPOGRAPHY, SURFACE HYDROLOGY, AND CLIMATE

F.E. Warren AFB is topographically positioned in the transition area between the eastern slope of the Rocky Mountains to the west and the High Plains to the east. The surface topography at the Base is characterized by rolling hills.

The ground surface topography at LF-03 is shown on Figure 3.1. Numerous surface depressions from landfill operations are present. An earthen berm defines the eastern boundary of the landfill. To the east of LF-03, the ground surface gradually slopes toward Crow Creek. Numerous seldom-used dirt roads cross the landfill area.

Surface water at LF-03 results from groundwater discharge and rainfall or snowmelt runoff. Surface water at the site flows to Crow Creek, located 2,000 feet downgradient from (east of) LF-03 (Figure 3.1). Crow Creek, which flows toward the southeast, is a gaining stream on the Base, predominantly as a result of contributing seeps. Crow Creek is fed by two upstream tributaries: an unnamed tributary and Diamond Creek. This creek system drains most of the southern portion of the Base (Ebasco, 1995). Stream discharge measurements were collected between April 1987 and May 1994 near the downstream boundary of the Base. Stream flow in Crow Creek, including inflow from Diamond Creek and the unnamed tributary, ranged from 0.79 to 15.30 cubic feet per second (ft^3/s).

The climate in the Cheyenne area is considered semiarid, typical of grassland prairies (Martner, 1986). The average annual precipitation for the time period 1961-1990 in

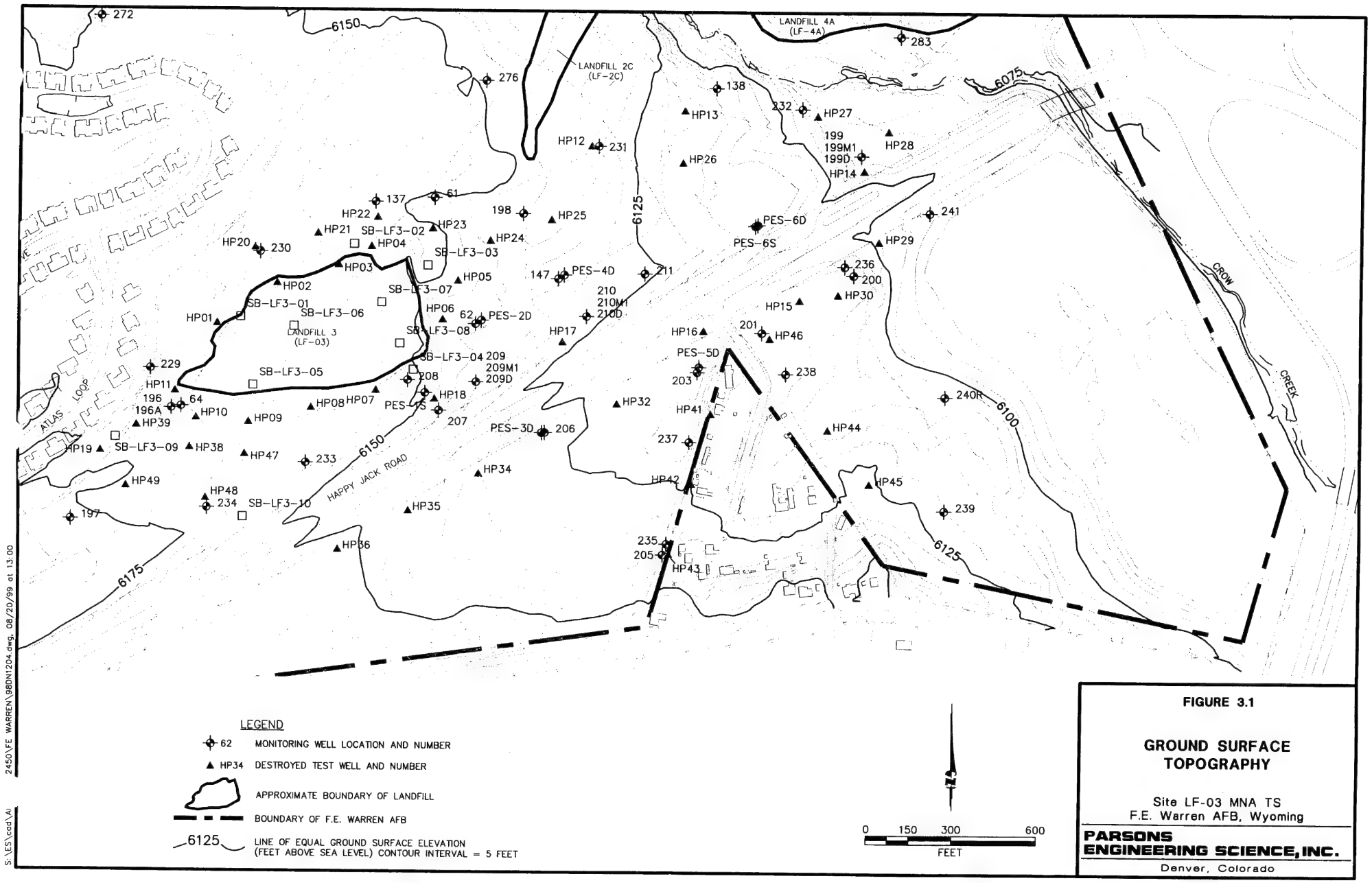

FIGURE 3.1

GROUND SURFACE TOPOGRAPHY

Site LF-03 MNA TS
F.E. Warren AFB, Wyoming

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

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Cheyenne was 13.31 inches (National Oceanic and Atmospheric Administration [NOAA], 1990). The average annual evaporation during the time period 1956-1970 was 62.83 inches, on the basis of a class-A pan measurement (Martner, 1986). Temperatures in Cheyenne range from below zero to about 90 degrees Fahrenheit (°F). The average daily mean temperature is 45.7 °F. Wind velocities are highest during the fall and winter, and lowest during the summer. The average hourly wind velocity is 13.7 miles per hour (mph) (Martner, 1986).

3.2 REGIONAL GEOLOGY AND HYDROGEOLOGY

3.2.1 Regional Geology

The regional geology of F.E. Warren AFB consists of approximately 25 feet of Quaternary deposits underlain by the Ogallala and White River Formation of Tertiary age. A regional geologic cross-section is presented on Figure 3.2. The Quaternary-age surficial deposits underlying F.E. Warren AFB consist of clay, silt, sand, gravel, cobbles, and boulders; these deposits are thickest along the streams. The surficial Quaternary deposits are hydraulically connected to the underlying Ogallala Formation.

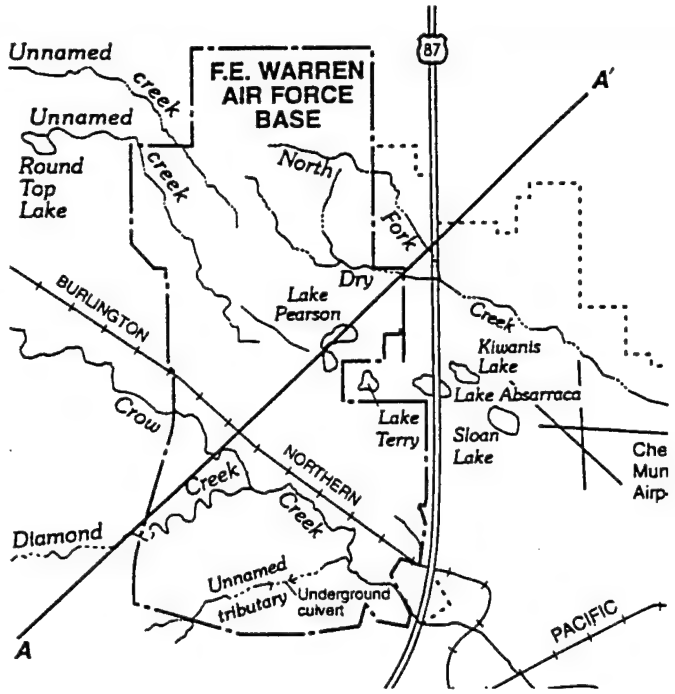
The major mode of deposition of the Ogallala Formation was fluvial with minor periods of local eolian deposition. Gutentag (1984) describes the Ogallala Formation as having been deposited by braided streams in a humid alluvial-fan environment. The Ogallala Formation consists of heterogeneous layers of slightly consolidated sand and gravel lenses interbedded with clay and silt. Sandstone and conglomerate beds also are present in the Ogallala Formation. The Ogallala Formation has a northwest strike, and dips to the northeast at about 52 feet per mile.

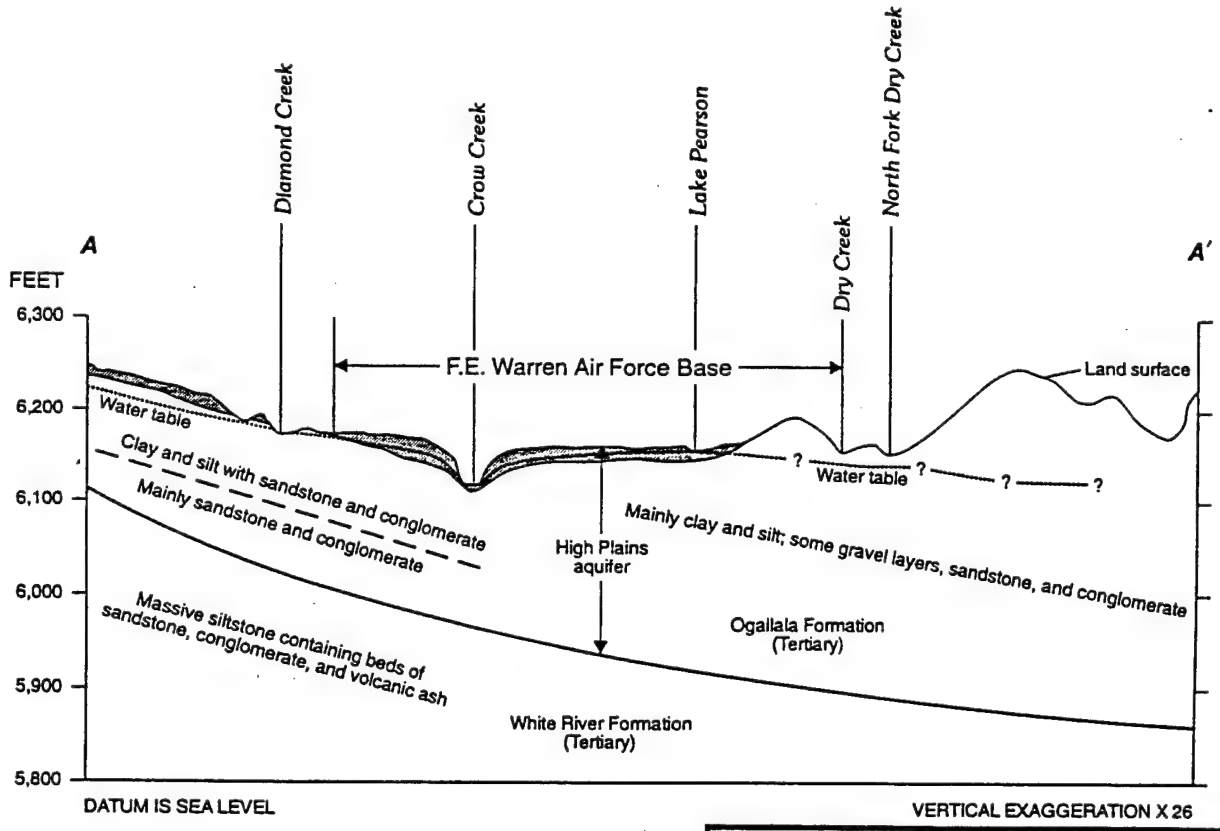
Underlying the Ogallala Formation at an approximate depth of 200 feet below ground surface (bgs) is the White River Formation. The White River Formation consists of pinkish-brown, massive siltstone containing beds of sandstone, conglomerate, and volcanic ash (USAF, 1991), and has approximately the same strike and dip as the Ogallala Formation. The thickness of the White River Formation is estimated to be 600 feet in the vicinity of the Base.

3.2.2 Regional Hydrogeology

The Quaternary deposits and the Ogallala Formation form the High Plains aquifer at the Base. The High Plains aquifer, which includes additional formations and extends into Nebraska and Colorado, is the principal source of water for most of the water-supply wells in the area near the Base (USAF, 1991).

The shallow groundwater surface in the High Plains aquifer is near the land surface in the vicinity of streams and deeper at locations further away from discharge areas. The direction of groundwater flow in the shallow zone of the High Plains aquifer is generally toward discharge areas such as Crow Creek, Diamond Creek, and the unnamed tributary to Crow Creek. In the southern portion of the Base, depth to shallow groundwater ranges from approximately 10 to 40 feet bgs (Ebasco, 1995).





LEGEND

- QUATERNARY DEPOSITS - CONSISTS OF CLAY, SILT SAND., COBBLES, GRAVEL. AND BOULDERS
- GEOLOGIC CONTACT - APPROXIMATELY LOCATED
- APPROXIMATELY LITHOFACIES CONTACT
- BOUNDARY OF F.E. WARREN AIR FORCE BASE
- A — A' LINE OF HYDROGEOLOGIC SECTION

Source: Ebasco, 1995 (Drawings not to scale).

FIGURE 3.2

REGIONAL HYDROGEOLOGIC CROSS-SECTION

Site LF-03 MNA TS
F.E. Warren Air Force Base, Wyoming

PARSONS
PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

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Groundwater on the Base is recharged locally by infiltration of precipitation; however, as a result of the dry climate, recharge from precipitation occurs only periodically. Groundwater on the Base is discharged through evapotranspiration and seepage into streams via springs and seeps.

3.3 SITE LF-03 GEOLOGY AND HYDROGEOLOGY

3.3.1 Site Geology

The lithology of LF-03 is characteristic of regional Quaternary-age surficial deposits and underlying deposits of the Ogallala Formation. These deposits consist of interbedded clay, silt, sand, gravel, and cobbles. At well 196, the Quaternary-age surficial deposits and the underlying Ogallala Formation were penetrated to the maximum drilled depth of 94 feet bgs (Appendix B).

Stratigraphy through the center of the site is depicted in two hydrogeologic cross-sections through LF-03 (Figure 3.3). Cross-section A-A' (Figure 3.4) is drawn in the approximate direction of groundwater flow, while cross-section B-B' (Figure 3.5) illustrates the stratigraphy perpendicular to cross-section A-A' and to the approximate direction of groundwater flow.

Stratigraphy across the LF-03 area is a heterogeneous, seemingly random mixture of interbedded clay, silt, sand, and gravel lithologies. Approximately 5 to 20 feet of fine-grained surficial deposits overlay silt, sand, and gravel of the Ogallala Formation. The interbedded clay, silt sand and gravel of the Ogallala Formation are characteristic of the braided channel depositional environment in which these units were deposited.

3.3.2 Site Hydrogeology

Results from drilling operations at LF-03 have not identified any uniform confining layers within the Ogallala Formation. Thus, shallow groundwater at the site is unconfined. However, vertical migration may be limited locally by the presence of less permeable clay layers. The direction and rate of groundwater flow were estimated from water level data and aquifer test results conducted in May 1999. Groundwater elevations measured in May 1999 are shown on Figure 2.2, with depth to groundwater in the vicinity of LF-03 ranging from 1.59 to 39.74 feet bgs. The direction of groundwater flow at LF-03 is east-northeast, toward Crow Creek (Figure 3.6). The hydraulic gradient at LF-03 ranges from 0.008 foot per foot (ft/ft) immediately east of the landfill, to 0.04 ft/ft further downgradient of the landfill towards Crow Creek (Figure 3.6). The average hydraulic gradient across the site is 0.02 ft/ft.

To assess the potential for a vertical component of flow, groundwater elevations measured at four well clusters for May 1999 were compared. These clusters include the following groups of monitoring wells (listed in order from shallowest screened depth to deepest screened depth): 196/196A/64; 209/209M1/209D; 210/210M1/210D; PES-6S and PES-6D; and 199/199M1/199D. Calculated vertical gradients are as follows:

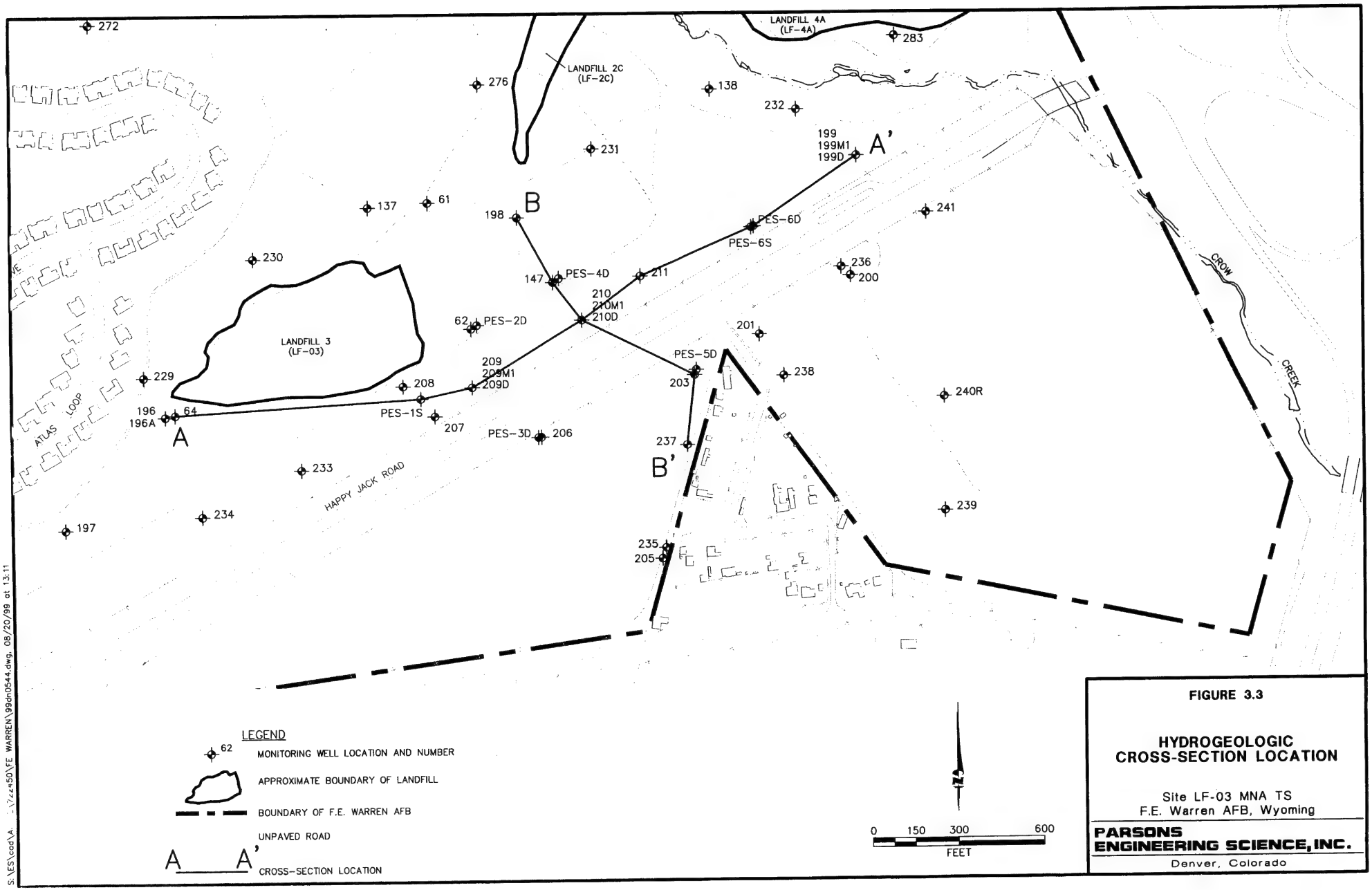

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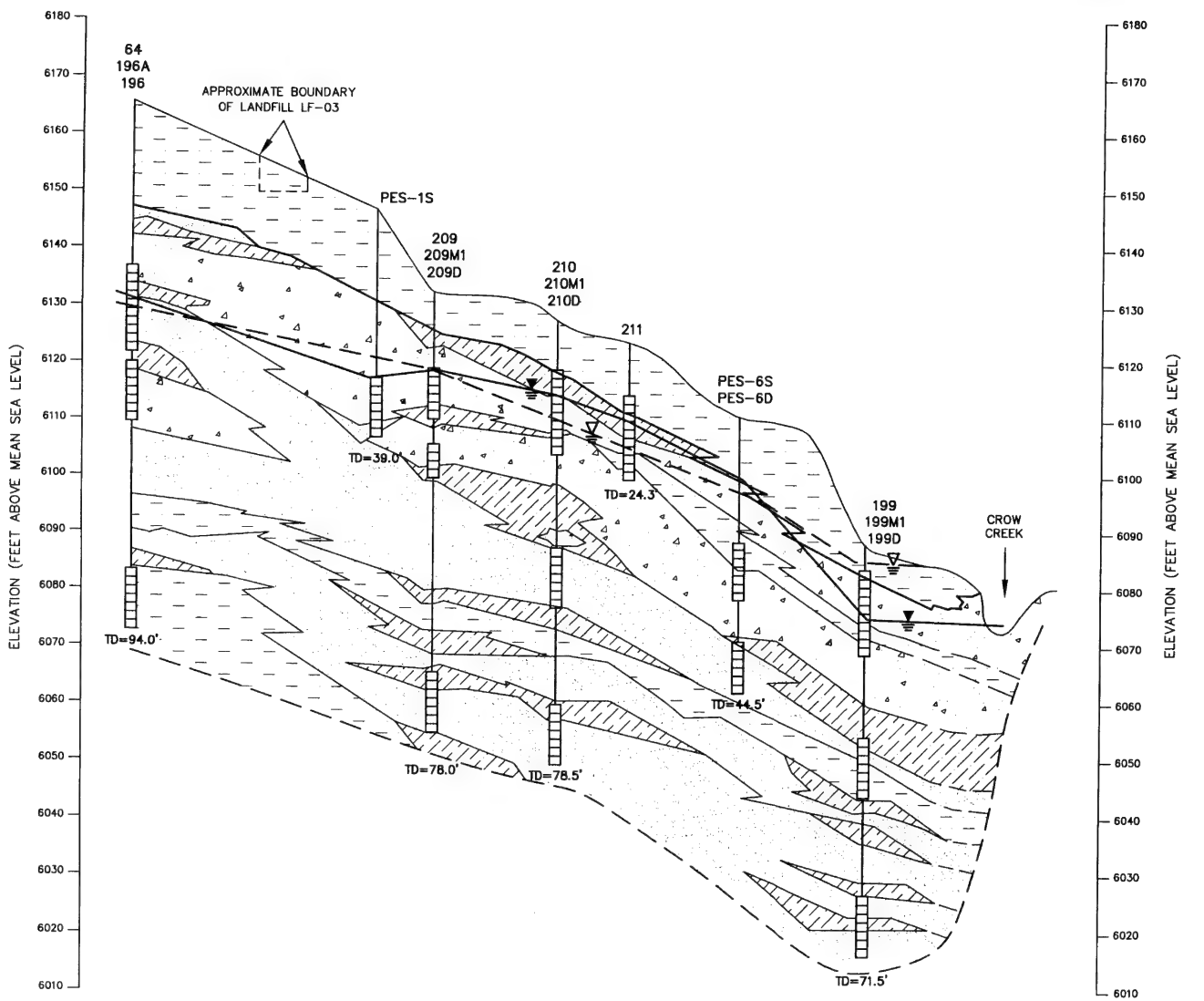
FIGURE 3.3

HYDROGEOLOGIC CROSS-SECTION LOCATION

Site LF-03 MNA TS
F.E. Warren AFB, Wyoming

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado



LEGEND

- FINE TO MEDIUM SAND, SOME GRAVEL, SOME SILT, WEATHERED
- SILTY SAND TO CLAYEY SAND
- SANDY SILT, SILT, AND CLAY
- SILTSTONE/MUDSTONE/CLAYSTONE
- SHALLOW GROUNDWATER SURFACE ELEVATION (MAY 1999)
- DEEP GROUNDWATER POTENTIOMETRIC SURFACE FOR MONITORING WELLS 196, 209D, 210D, PES-6D, AND 199D (MAY 1999)
- MONITORING WELL WITH SCREENED INTERVAL
- LITHOLOGIC CONTACT DASHED WHERE INFERRED

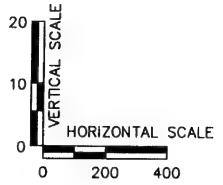


FIGURE 3.4

HYDROGEOLOGIC CROSS-SECTION A-A'

Site LF-03 MNA TS
F.E. Warren AFB, Wyoming

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

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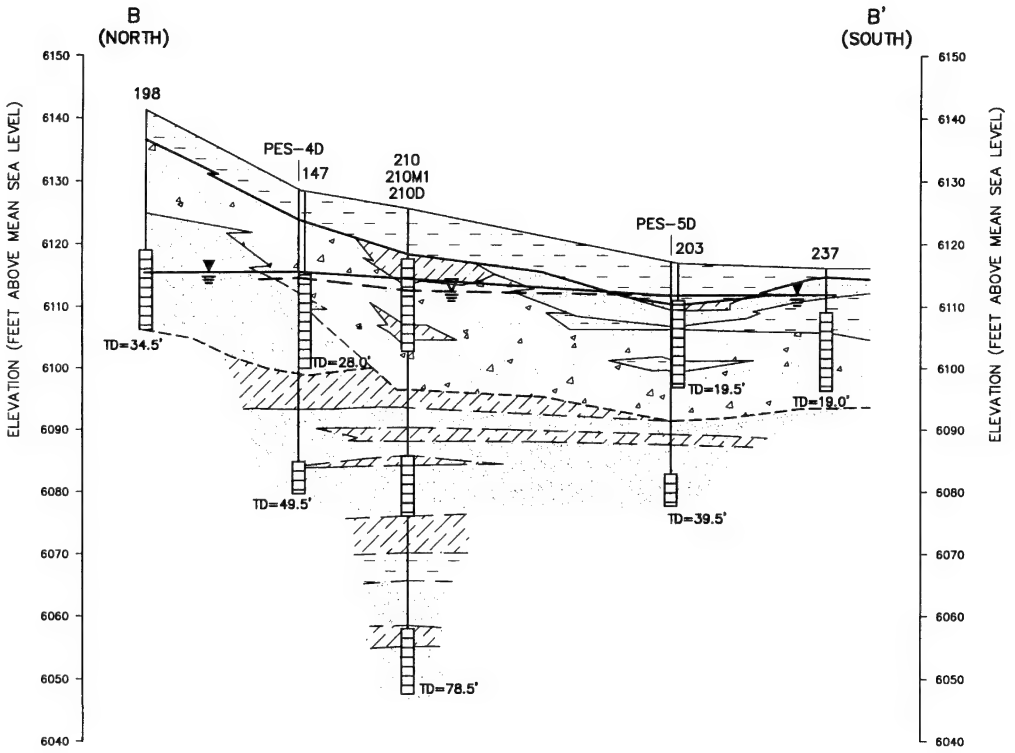

LEGEND

- FINE TO MEDIUM SAND, SOME GRAVEL, SOME SILT, WEATHERED
- SILTY SAND TO CLAYEY SAND
- SANDY SILT, SILT, AND CLAY
- SILTSTONE/MUDSTONE/CLAYSTONE
- SHALLOW GROUNDWATER SURFACE ELEVATION (MAY 1999)
- DEEP GROUNDWATER POTENTIOMETRIC SURFACE FOR MONITORING WELLS PES-4D, 210 MI, AND PES-5D (MAY 1999)
- MONITORING WELL WITH SCREENED INTERVAL
- LITHOLOGIC CONTACT DASHED WHERE INFERRED

NOTE:
ALL ELEVATIONS SHOWN ARE IN NGVD 29. TO CONVERT TO NAVD 88 ADD 3.32 FEET.

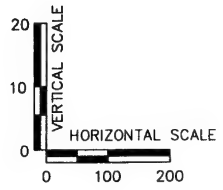

FIGURE 3.5

HYDROGEOLOGIC CROSS-SECTION B-B'

Site LF-03 MNA TS
F.E. Warren AFB, Wyoming

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

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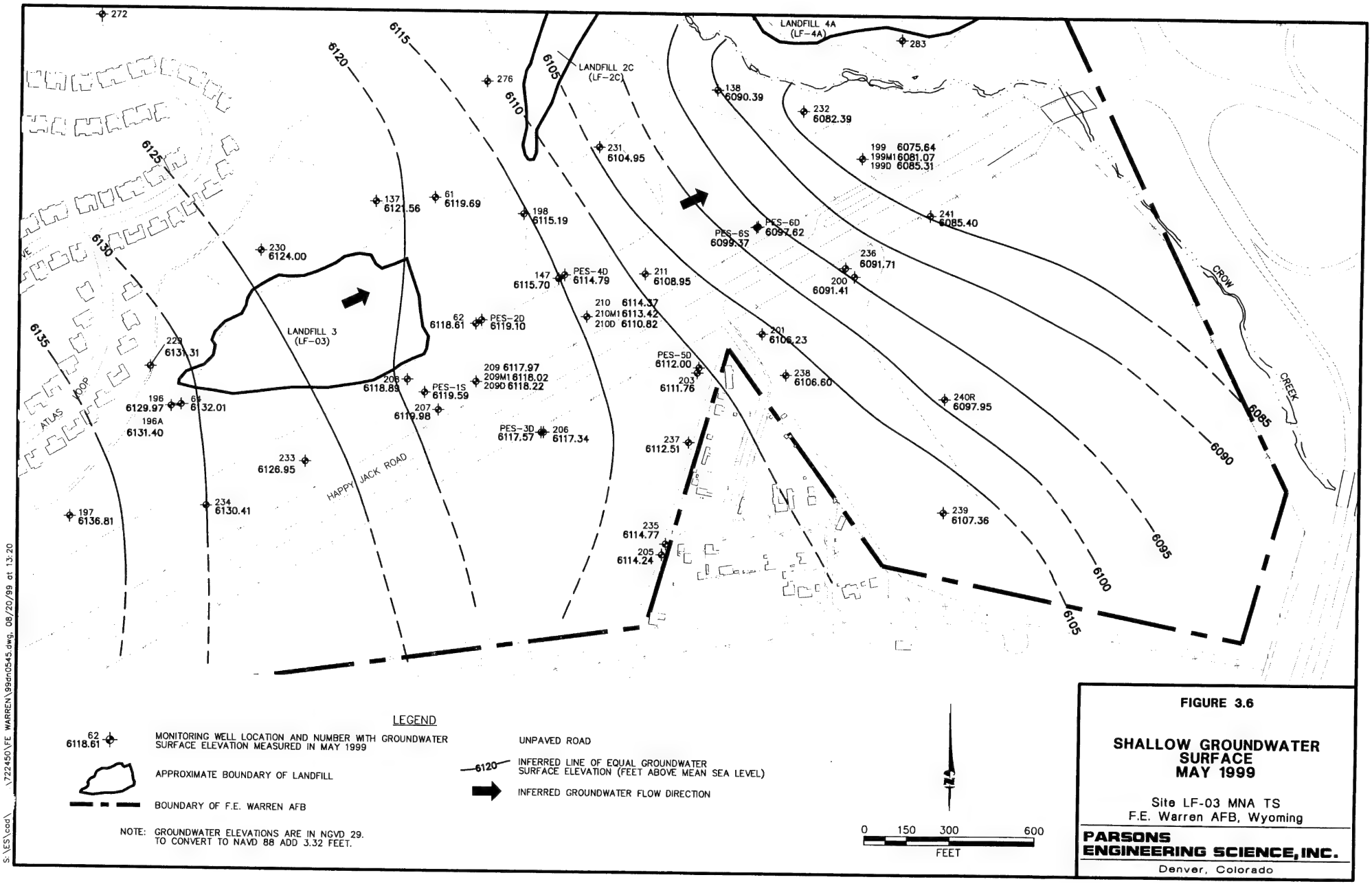

LEGEND

62 6118.61 — MONITORING WELL LOCATION AND NUMBER WITH GROUNDWATER SURFACE ELEVATION MEASURED IN MAY 1999

APPROXIMATE BOUNDARY OF LANDFILL

BOUNDARY OF F.E. WARREN AFB

NOTE: GROUNDWATER ELEVATIONS ARE IN NGVD 29. TO CONVERT TO NAVD 88 ADD 3.32 FEET.

UNPAVED ROAD

6120 — INFERRED LINE OF EQUAL GROUNDWATER SURFACE ELEVATION (FEET ABOVE MEAN SEA LEVEL)

INFERRED GROUNDWATER FLOW DIRECTION

0 150 300 600
FEET

FIGURE 3.6

SHALLOW GROUNDWATER SURFACE MAY 1999

Site LF-03 MNA TS
F.E. Warren AFB, Wyoming

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

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- Well cluster 196/196A/64 is located upgradient from the potential source area, southwest of LF-03. Based on groundwater elevation data collected in 1999, the vertical groundwater gradient at well cluster 196/196A/64 is 0.04 ft/ft in a downward direction.

- Well cluster 209/209M1/209D is located directly downgradient from the TCE source area, along the plume axis. The vertical gradient at well cluster 209/209M1/209D is approximately zero (less than 0.01 ft/ft).

- Well cluster 210/210M1/210D is located downgradient along the plume axis. The vertical gradient at well cluster 210/210M1/210D is 0.05 ft/ft in a downward direction.

- Well cluster PES-6S/PES-6D is located further downgradient along the plume axis. The vertical gradient at well cluster PES-6S/PES-6D is 0.12 ft/ft in a downward direction.

- Well cluster 199/199M1/199D is the furthest downgradient well cluster, located 300 feet west of Crow Creek. The vertical gradient at 199/199M1/199D is +0.20 ft/ft in an upward direction.

Observed vertical gradients for well pairs 196/196A/64, 209/209M1/209D, 210/210M1/210D, and 199/199M1/199D were similar to those calculated from measurements collected in June 1996 (Parsons ES, 1999). Information collected from these well-clusters suggests that Crow Creek, which is east of LF-03, is influencing local groundwater flow by changing the overall vertical gradient from a downward to an upward vertical gradient closer to the creek, a condition indicating groundwater discharge to Crow Creek.

Slug tests were performed to determine the horizontal hydraulic conductivity in the vicinity of LF-03. Results of the slug tests performed by Parsons ES are summarized on Table 3.1, and slug test analyses are included in Appendix B. Average hydraulic conductivities for individual wells at LF-03 range from 0.03 feet per day (ft/day) at PES-3D and PES-5D, to 4.46 ft/day at PES-1S. The geometric mean of the average hydraulic conductivities is 0.19 ft/day. The range of hydraulic conductivities calculated for LF-03 during this TS correspond to literature values of hydraulic conductivity reported for fine sand and silt (Spitz and Moreno, 1996).

The effective porosity of a given lithology is a measure of the amount of void space available for fluid flow through the lithologic unit. Effective porosity for the silt and sand interval at LF-03 is estimated to be approximately 20 percent, based on accepted literature values (Spitz and Moreno, 1996) and the range of estimated hydraulic conductivities (Table 3.1). However, effective porosity can be reduced by localized intervals of cementation or fine-grained deposits.

Assuming isotropic horizontal hydraulic conductivity, the advective velocity of groundwater in the direction of maximum hydraulic gradient is given by:

TABLE 3.1

HYDRAULIC CONDUCTIVITIES AND AVERAGE GROUNDWATER VELOCITIES

SITE LF-03 MNA TS

F.E. WARREN AFB, WYOMING

Monitoring Well	Test Date	Screened Interval Elevation (ft bgs)[a/]	Test Number	Hydraulic Conductivity (K) (ft/day)[b/]	(cm/sec)[c/]	(gpd/ft^2)[d/]	Estimated Effective Porosity	Hydraulic Gradient (ft/ft)[e/]	Groundwater Velocity (ft/yr)[f/]
PES-1S	May-99	29.0-39.0	1	3.29	1.16E-03	24.6	0.20	0.02	120.1
			2	4.55	1.61E-03	34.0	0.20	0.02	166.1
			3	4.53	1.60E-03	33.9	0.20	0.02	165.3
			4	5.47	1.93E-03	40.9	0.20	0.02	199.7
		Average at PES-1S		4.46	1.57E-03	33.4	0.20	0.02	162.8
PES-2D	May-99	39.5-49.5	1	0.18	6.35E-05	1.3	0.20	0.02	6.6
			2	0.19	6.71E-05	1.4	0.20	0.02	6.9
			3	0.18	6.35E-05	1.3	0.20	0.02	6.6
			4	0.19	6.71E-05	1.4	0.20	0.02	6.9
		Average at PES-2D		0.19	6.53E-05	1.4	0.20	0.02	6.8
PES-3D	May-99	34.0-39.0	1	0.03	1.06E-05	0.2	0.20	0.02	1.1
		Average at PES-3D		0.03	1.06E-05	0.2	0.20	0.02	1.1
PES-4D	May-99	44.5-49.5	1	0.05	1.77E-05	0.4	0.20	0.02	1.8
			2	0.08	2.82E-05	0.6	0.20	0.02	2.9
			3	0.57	2.01E-04	4.3	0.20	0.02	20.8
		Average at PES-4D		0.23	8.24E-05	1.7	0.20	0.02	8.5
PES-5D	May-99	34.5-39.5	1	0.03	1.06E-05	0.2	0.20	0.02	1.1
		Average at PES-5D		0.03	1.06E-05	0.2	0.20	0.02	1.1
PES-6S	May-99	22.0-32.0	1	0.09	3.18E-05	0.7	0.20	0.02	3.3
			2	0.08	2.82E-05	0.6	0.20	0.02	2.9
			3	0.11	3.88E-05	0.8	0.20	0.02	4.0
		Average at PES-6S		0.09	3.29E-05	0.7	0.20	0.02	3.4
PES-6D	May-99	39.5-44.5	1	1.37	4.84E-04	10.2	0.20	0.02	50.0
			2	0.27	9.53E-05	2.0	0.20	0.02	9.9
			3	0.02	7.06E-06	0.1	0.20	0.02	0.7
		Average at PES-6D		0.55	1.95E-04	4.1	0.20	0.02	20.2
		Geometric Mean of Averages		**0.19**	**6.71E-05**	**1.4**	**0.20**	**0.02**	**6.9**

[a/] ft bgs = Feet below ground surface.

[b/] ft/day = Feet per day.

[c/] cm/sec = Centimeters per second.

[d/] gpd/ft^2 = Gallons per day per square foot.

[e/] ft/ft = Foot per foot.

[f/] ft/yr = Feet per year.

$$\bar{v} = \frac{K}{n_e}\frac{dH}{dL}$$

Where: $\bar{v}$ = Average advective groundwater velocity (seepage velocity) [L/T]

K = Hydraulic conductivity [L/T]

dH/dL = Lateral hydraulic gradient [L/L]

n_e = Effective porosity.

Using the range of hydraulic conductivity (0.03 to 4.46 ft/day), an average horizontal hydraulic gradient of 0.02 ft/ft, and an estimated effective porosity of 0.20 for fine-grained sand, the advective groundwater flow velocity in the shallow saturated zone at LF-03 is calculated to be approximately 1.1 to 163 feet per year (ft/yr). Using a geometric mean of the average hydraulic conductivity calculated for each well (0.19 ft/day), an average groundwater velocity of 6.9 ft/yr is calculated for the site.

Preferential flow paths may be locally present due to variations in lithogy and the corresponding variation in permeability at LF-03. Preferential flow paths were not apparent based on data collected in 1999. However, use of an average groundwater velocity of 0.19 ft/yr may be non-conservative when evaluating contaminant transport and contaminant velocities. Further consideration of spatial changes in hydraulic gradient, hydraulic conductivity, and contaminant transport velocity are presented in Section 5, Groundwater Flow and Contaminant Transport Model.

3.4 GROUNDWATER USE

Groundwater from the shallow aquifer at F.E. Warren AFB is not extracted for beneficial use. Groundwater underlying the Nob Hill development has not been pumped for potable use since residents of the Nob Hill neighborhood were added to the city water system in July 1997.

3.5 POTENTIAL PATHWAYS AND RECEPTORS AT LF-03

The potential pathway of current concern for groundwater at LF-03 is migration to either Crow Creek or off-Base wells. The nearest Base property boundary in the downgradient direction is located approximately 1,100 feet east of the inferred source area. Dissolved contaminants have historically been detected in monitoring well 203, which is adjacent to the west side of the Nob Hill development. TCE is the only CAH that has historically been identified at a concentration greater than its federal USEPA maximum contaminant level (MCL) in the off-Base area of Nob Hill. Potential exposure to dissolved contaminants migrating from LF-03 also could occur as a result of groundwater discharging to Crow Creek. Crow Creek exits the Base northeast of LF-03 via a culvert under the main highway.

SECTION 4

CONTAMINANT DISTRIBUTION AND EVIDENCE FOR BIODEGRADATION

Soil and groundwater have been contaminated as a result of waste disposal activities at LF-03. Work during the RI (Ebasco, 1995) focused on defining the nature and extent of contamination at the site. Additional compliance work is currently being conducted by EarthTech. The data collected during those efforts are used to supplement the TS field investigation results presented in the following subsections. In particular, this section focuses on data useful for evaluating and modeling natural attenuation of CAHs dissolved in groundwater, including a summary of hydrocarbon degradation.

4.1 OVERVIEW OF HYDROCARBON BIODEGRADATION

Primary mechanisms for natural attenuation of CAHs include biodegradation, dispersion, dilution from recharge and upgradient flow, sorption, and volatilization. Of these processes, biodegradation is the only mechanism working to transform contaminants into ultimately innocuous byproducts. When indigenous microorganisms work to bring about a reduction in the total mass of contamination in the subsurface without the addition of nutrients, these biodegradation processes are considered intrinsic.

To provide a foundation for site interpretations, the following subsections review the major bioremediation processes that act upon CAHs. Chlorinated solvents are the primary groundwater contaminants at LF-03. A generalized review of the biodegradation processes is presented first, with subsequent sections focusing on biodegradation of CAHs.

4.1.1 Review of Biodegradation Processes

Microorganisms obtain energy for cell production and maintenance by facilitating thermodynamically advantageous reduction/oxidation (redox) reactions involving the transfer of electrons from electron donors to available electron acceptors. This results in the oxidation of the electron donor and the reduction of the electron acceptor. Electron donors may be natural organic carbon, fuel hydrocarbon compounds (e.g., BTEX), and less-chlorinated solvents (e.g., VC, DCE, dichloroethane [DCA], or chlorinated benzenes ranging from chlorobenzene [CB] to tetrachlorobenzene [TeCB]). Fuel hydrocarbons or solvents are completely degraded or detoxified if they are utilized as the primary electron donor (i.e., as a primary substrate or carbon source) for microbial metabolism (Bouwer, 1992). Electron acceptors are elements or compounds that occur in relatively oxidized states, and include oxygen, nitrate, ferric iron, sulfate, manganese, carbon dioxide, and

highly chlorinated solvents [e.g., PCE, TCE, tetrachloroethane (PCA), trichloroethane (TCA), and polychlorinated benzenes].

The driving force of biodegradation is electron transfer, which is quantified by the Gibbs free energy of the reaction ($\Delta G°_r$) (Stumm and Morgan, 1981; Bouwer, 1994; Godsey, 1994). The value of $\Delta G°_r$ represents the quantity of free energy consumed ($\Delta G°_r > 0$) or yielded ($\Delta G°_r < 0$) to the system during the reaction. Although thermodynamically favorable, most of the reactions involved in biodegradation of fuel hydrocarbons or CAHs cannot proceed abiotically due to a lack of activation energy. Microorganisms are capable of providing the necessary activation energy; however, they will facilitate only those redox reactions that have a net yield of energy (i.e., $\Delta G°_r < 0$). Most reactions involving biodegradation of contaminants do yield energy to the microbes. However, specific geochemical conditions are often necessary for biodegradation reactions, which allow the appropriate microbial population to develop and grow.

Microorganisms preferentially utilize electron acceptors while metabolizing hydrocarbons (Bouwer, 1992). DO is utilized first as the prime electron acceptor where present. It is under aerobic conditions that fuel hydrocarbons and the less chlorinated solvents are most commonly used as electron donors. After the DO is consumed, anaerobic microorganisms use native electron acceptors (as available) in the following order of preference: nitrate, manganese, ferric iron hydroxide, sulfate, and finally carbon dioxide. Under anaerobic conditions, BTEX compounds and other fuel hydrocarbons are still used as electron donors. Chlorinated solvents that are amenable to reductive dehalogenation are generally used as electron acceptors when aquifer conditions are such that sulfate or carbon dioxide is the preferred electron acceptor. Because the biodegradation of fuel hydrocarbons and CAHs can deplete the concentrations of electron acceptors, examining the distribution of electron acceptor concentrations can provide evidence of whether biodegradation is occurring and the degree to which it is occurring.

The expected sequence of redox reactions in an aquifer is also a function of the ORP of the groundwater. ORP is a measure of the relative tendency of a solution or chemical reaction to accept or transfer electrons, and it can be used as an indicator of which redox reactions are operating at a site. As each subsequent electron acceptor is utilized, the groundwater becomes more reducing, and the redox potential of the water decreases. Microbial mediated redox reactions are the main driving force for ORP decreases.

Depending on the types and concentrations of electron acceptors present (e.g., nitrate, sulfate, carbon dioxide), pH conditions, and redox potential, anaerobic biodegradation can occur by denitrification, ferric iron reduction, sulfate reduction, or methanogenesis. Other, less common anaerobic degradation mechanisms such as manganese or nitrate reduction may dominate if the physical and chemical conditions in the subsurface favor use of these electron acceptors. Vroblesky and Chapelle (1995) show that the dominant terminal electron accepting process can vary both temporally and spatially in an aquifer.

4.1.2 Biodegradation of Chlorinated Solvents

Chlorinated solvents can be transformed, directly or indirectly, by biological processes (e.g., Bouwer *et al.*, 1981; Miller and Guengerich, 1982; Reineke and Knackmuss, 1984; Wilson and Wilson, 1985; de Bont *et al.*, 1986; Nelson *et al.*, 1986; Spain and Nishino,

1987; Bouwer and Wright, 1988; Little *et al.*, 1988; Mayer *et al.*, 1988; Arciero *et al.*, 1989; Cline and Delfino, 1989; Freedman and Gossett, 1989; Folsom *et al.*, 1990; Harker and Kim, 1990; Alvarez-Cohen and McCarty, 1991a, 1991b; DeStefano *et al.*, 1991; Henry, 1991; Sander *et al.*, 1991; McCarty *et al.*, 1992; Hartmans and de Bont, 1992; Chapelle, 1993; McCarty and Semprini, 1994; Vogel, 1994; Suflita and Townsend, 1995; Bradley and Chapelle, 1996; Klier *et al.*, 1996; Spain, 1996). Biodegradation of chlorinated solvents (or CAHs) and chlorinated benzenes results from the same general processes that bring about biodegradation of fuel hydrocarbons. However, a more complex series of processes often is involved, and CAHs and chlorinated benzenes may act as either substrates (electron donors) or electron acceptors depending upon what geochemical conditions prevail.

Whereas fuel hydrocarbons are biodegraded in essentially one step by acting as an electron donor/carbon source, CAHs and chlorinated benzenes may undergo several types of biodegradation involving multiple steps. CAHs may undergo biodegradation through three different pathways: use as an electron acceptor, use as an electron donor, or cometabolism, which is degradation resulting from exposure to a catalytic enzyme fortuitously produced during an unrelated process. At a given site, one or all of these processes may be operating, although at many sites the use of CAHs as electron acceptors appears to be the most likely.

In a pristine aquifer, native organic carbon is utilized as an electron donor and DO is utilized first as the prime electron acceptor. Where anthropogenic carbon (e.g., fuel hydrocarbons, less-chlorinated CAHs, or chlorinated benzenes with four or fewer chlorines) is present, it also may be utilized as an electron donor. Most chlorinated solvents that can act as electron donors have thus far only been demonstrated to do so under aerobic conditions, with the notable exception of VC (Bradley and Chapelle, 1996). After the DO is consumed, anaerobic microorganisms typically use native electron acceptors (as available) in the following order of preference: nitrate, ferric iron oxyhydroxide, sulfate, and finally carbon dioxide. Evaluation of the distribution of these electron acceptors can provide evidence of where and how CAH biodegradation is occurring. In addition, because CAHs may be used as electron acceptors or electron donors (in competition with other acceptors or donors), maps showing the distribution of these compounds also will provide evidence of the types of biodegradation processes acting at a site. A more complete description of the main types of biodegradation reactions affecting CAHs dissolved in groundwater is presented in the following subsections.

4.1.2.1 Electron Acceptor Reactions (Reductive Dehalogenation)

Under anaerobic conditions, biodegradation of chlorinated solvents usually proceeds through a process called reductive dehalogenation. During this process, the halogenated hydrocarbon is used as an electron acceptor, not as a source of carbon, and a chloride atom is removed and replaced with a hydrogen atom. The transformation of chlorinated ethenes via reductive dehalogenation is illustrated in Figure 4.1. In general, reductive dehalogenation of chlorinated ethenes occurs by sequential dehalogenation from PCE to TCE to DCE to VC to ethene. An analogous pattern for chlorinated ethanes might be

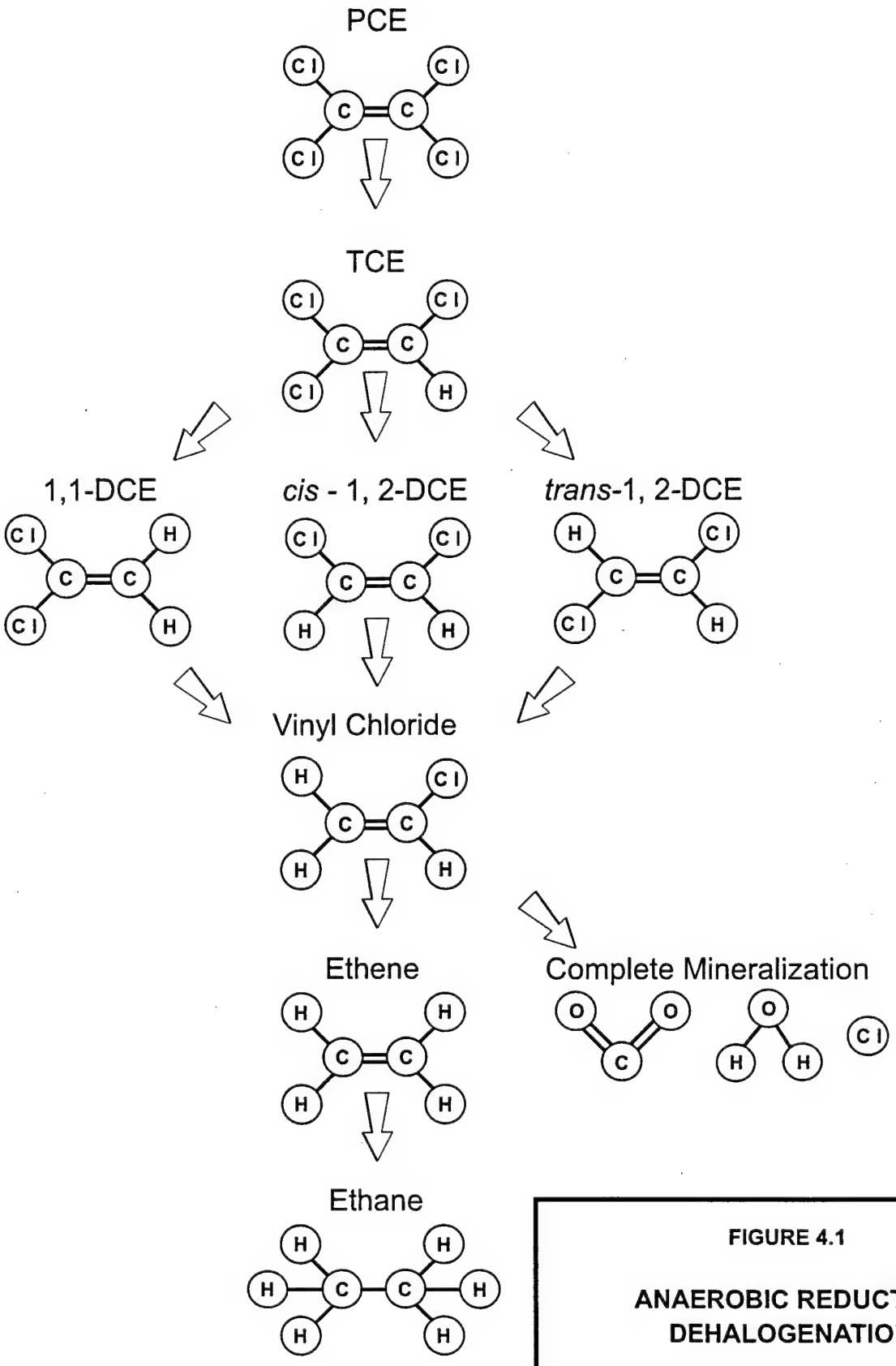

FIGURE 4.1

ANAEROBIC REDUCTIVE DEHALOGENATION

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PCA to TCA to DCA to CA, and for chlorinated benzenes the pattern might be TeCB to trichlorobenzene (TCB) to dichlorobenzene (DCB) to CB. Depending upon environmental conditions, these sequences may be interrupted, with other processes (e.g., aerobic or abiotic degradation) then acting upon the products. Reductive dehalogenation of chlorinated solvent compounds is associated with the accumulation of daughter products and an increase in chloride concentrations.

Reductive dehalogenation affects each of the chlorinated ethenes differently. Of the ethenes, PCE is the most susceptible to reductive dehalogenation because it is the most oxidized. Conversely, VC is the least susceptible to reductive dehalogenation, because it is the least oxidized of the ethene compounds. Likewise, hexachlorobenzene is more susceptible to reductive dehalogenation than less-chlorinated benzenes. In general, the rate of reductive dehalogenation of chlorinated solvents has been observed to decrease as the degree of chlorination decreases (Vogel and McCarty, 1985; Bouwer, 1994). Murray and Richardson (1993) have postulated that this rate decrease may explain the accumulation of VC in PCE and TCE plumes that are undergoing reductive dehalogenation.

Reductive dehalogenation also can be controlled by the redox conditions of the site groundwater system. In general, reductive dehalogenation has been demonstrated under anaerobic nitrate- and sulfate-reducing conditions, but the most rapid biodegradation rates, affecting the widest range of compounds, occur under methanogenic conditions (Bouwer, 1994). Dehalogenation of PCE and TCE to DCE can proceed under mildly reducing conditions such as nitrate reduction or ferric iron [iron (III)] reduction (Vogel *et al.*, 1987). However, the transformation of DCE to VC, or the transformation from VC to ethene requires more strongly reducing conditions (Freedman and Gossett, 1989; DeStefano *et al.*, 1991; De Bruin *et al.*, 1992).

Reductive dehalogenation of some compounds also can preferentially produce specific daughter compounds. For example, during reductive dehalogenation of TCE or PCE, all three isomers of DCE can theoretically be produced. However, Bouwer (1994) reports that under the influence of biodegradation, *cis*-1,2-DCE is a more common intermediate than *trans*-1,2-DCE, and that 1,1-DCE is the least prevalent intermediate of the three DCE isomers.

When chlorinated compounds are used as electron acceptors, there must be an appropriate source of carbon for microbial growth in order for reductive dehalogenation to occur (Bouwer, 1994). Potential carbon sources/electron donors can include low-molecular-weight compounds (e.g., lactate, acetate, methanol, or glucose) present in natural organic matter, fuel hydrocarbons, or less-chlorinated solvents (as discussed below).

4.1.2.2 Electron Donor Reactions

Under aerobic conditions some CAHs can be utilized as the primary substrate (i.e., electron donor) in biologically mediated redox reactions (McCarty and Semprini, 1994). In this type of reaction, the facilitating microorganism obtains energy and organic carbon from the degraded compound. In contrast to reactions in which the chlorinated

compound is used as an electron acceptor, only the least oxidized chlorinated solvents (e.g., VC or DCE) may be utilized as electron donors in biologically mediated redox reactions.

Microorganisms are generally believed to be incapable of growth using TCE and PCE, although other less chlorinated CAHs have been documented as substrates (Murray and Richardson, 1993). For example, Davis and Carpenter (1990) describe the aerobic oxidation of VC in groundwater, and McCarty and Semprini (1994) describe investigations in which VC and 1,2-DCA were shown to serve as primary substrates. Dichloromethane has the potential to function as a primary substrate under either aerobic or anaerobic environments (McCarty and Semprini, 1994), and all three DCE isomers can be mineralized under aerobic conditions (Klier *et al.*, 1996). In addition, Bradley and Chapelle (1996) show evidence of oxidation of VC under iron-reducing conditions as long as there is sufficient bioavailable iron (III). Aerobic metabolism of VC may be characterized by a loss of VC mass, a decreasing molar ratio of VC to other CAH compounds, and, rarely, the presence of chloromethane.

4.1.2.3 Cometabolism

When a chlorinated solvent is biodegraded through cometabolism, it serves as neither an electron acceptor nor a primary substrate in a biologically mediated redox reaction. Instead, an enzyme or cofactor that is fortuitously produced by organisms for other purposes catalyzes the degradation of the compound. The organism receives no known benefit from degradation of the solvent; rather the cometabolic degradation of the solvent may in fact be harmful to the microorganism responsible for the production of the enzyme or cofactor (McCarty and Semprini, 1994).

Cometabolism is best documented for chlorinated ethenes in aerobic environments, although it potentially could occur with other chlorinated solvents or under anaerobic conditions. Aerobic degradation pathways for chlorinated ethenes are illustrated in Figure 4.2. It has been reported that under aerobic conditions chlorinated ethenes, with the exception of PCE, are susceptible to cometabolic degradation (Murray and Richardson, 1993; Vogel, 1994; McCarty and Semprini, 1994). Vogel (1994) further elaborates that the cometabolism rate increases as the degree of dehalogenation decreases.

In the cometabolic process, bacteria indirectly transform TCE while they use BTEX or another carbon source to meet their energy requirements. TCE does not enhance the degradation of carbon sources, nor does its cometabolism interfere with the use of electron acceptors involved in the oxidation of those carbon sources. Given this relationship, it would follow that depletion of suitable substrates (BTEX or other organic carbon sources) likely limits cometabolism of CAHs.

4.1.2.4 Abiotic Degradation of Chlorinated Solvents

Chlorinated solvents dissolved in groundwater also may degrade by abiotic mechanisms, although the reactions may not be complete and often result in the formation of a toxic intermediate. The most common abiotic reactions affecting chlorinated solvents are hydrolysis and dehydrohalogenation. Hydrolysis is a

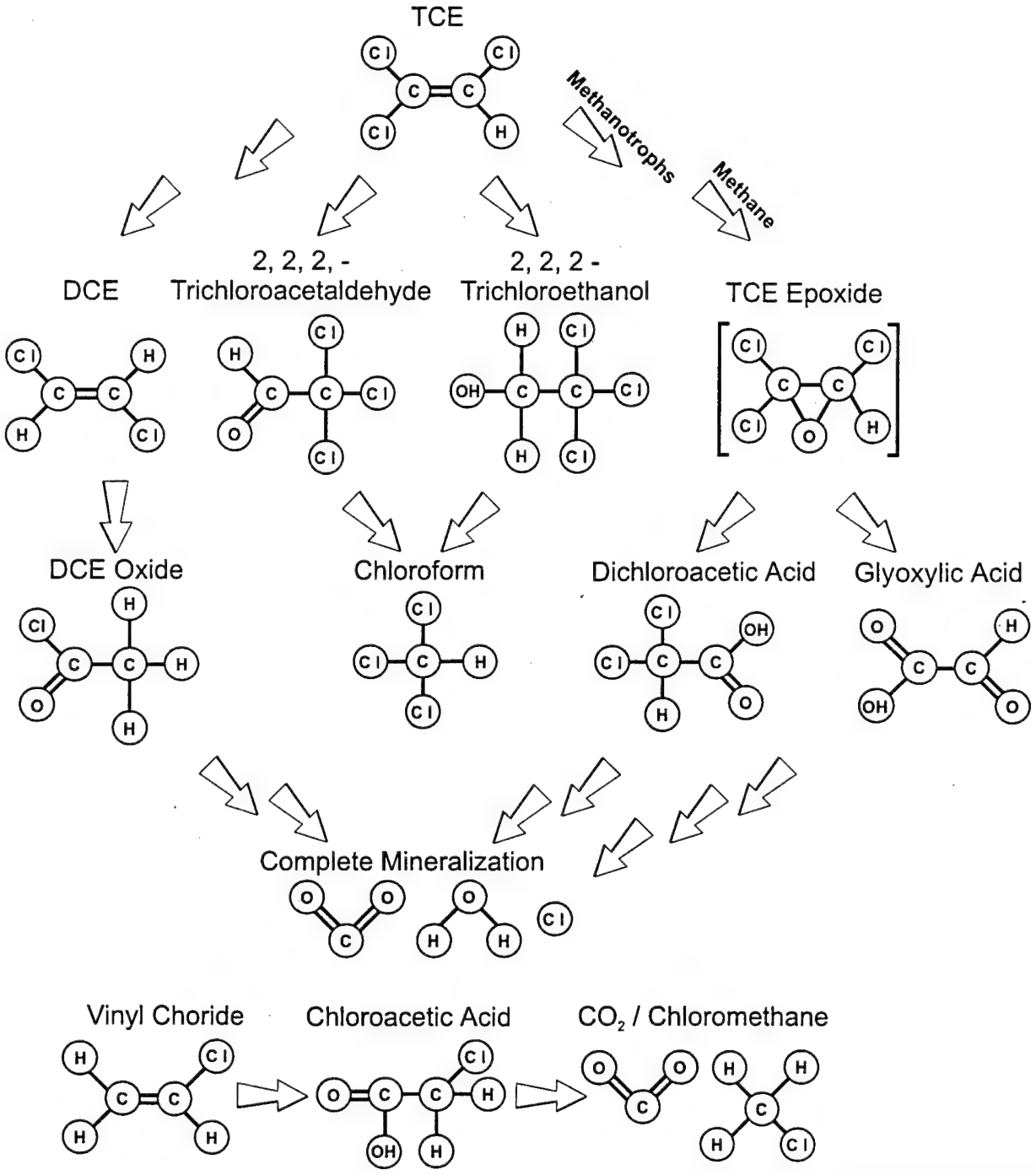

FIGURE 4.2

AEROBIC DEGRADATION PATHWAYS

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substitution reaction in which a halogen substituent is replaced with a hydroxyl (OH^-) group from a water molecule. Dehydrohalogenation is an elimination reaction in which a halogen is removed from a carbon atom, followed by removal of a hydrogen atom from an adjacent carbon atom, with a double bond between the carbon atoms being produced. Other possible reactions include oxidation and reduction, although no abiotic oxidation reactions involving common halogenated solvents have been reported in the literature (Butler and Barker, 1996).

Attributing changes in the presence, absence, or concentration of halogenated solvents to abiotic processes is usually difficult, particularly on the field scale (Butler and Barker, 1996). Solvents may undergo both biotic and abiotic degradation, and discerning the effects of each mechanism (on the field scale), if possible, is difficult. Also, the breakdown products of some reactions such as hydrolysis (e.g., acids and alcohols) may be further degraded (biotically or abiotically) to products which require additional analyses that may not be feasible for a field investigation (Butler and Barker, 1996). CAH hydrolysis has not been successfully demonstrated at the field scale (Butler and Barker, 1996). Evidence of dehydrohalogenation also is difficult to collect, although the presence of 1,1-DCE in conjunction with 1,1,1-TCA can provide a tentative indication that the process is ongoing. The presence of 1,1-DCE provides strong evidence of dehydrohalogenation where it is known that no DCE has been released.

4.1.3 Behavior of Chlorinated Solvent Plumes

Chlorinated solvent plumes can exhibit three types of behavior depending on the amount of solvent, the amount of organic (native and/or anthropogenic) carbon in the aquifer, the distribution and concentration of natural electron acceptors, and the types of electron acceptors being utilized. Individual plumes may exhibit all three types of behavior in different portions of the plume.

4.1.3.1 Type 1 Behavior

Type 1 behavior occurs where the primary substrate is anthropogenic carbon (e.g., BTEX or landfill leachate), and this anthropogenic carbon drives reductive dechlorination. When evaluating natural attenuation of a plume exhibiting Type 1 behavior the following questions must be answered:

1. Is the electron donor supply adequate to allow microbial reduction of the chlorinated organic compounds? In other words, will the microorganisms "strangle" before they "starve" [i.e., will they run out of CAHs (electron acceptors) before they run out of primary substrate (anthropogenic carbon)]?

2. What is the role of competing electron acceptors (e.g., DO, nitrate, iron (III) and sulfate)?

3. Are VC and other less-chlorinated solvents being oxidized, or are they being reduced?

Type 1 behavior results in the rapid and extensive degradation of the highly chlorinated solvents such as PCE, TCE, or polychlorinated benzenes.

4.1.3.2 Type 2 Behavior

Type 2 behavior dominates in areas characterized by relatively high concentrations of biologically available native organic carbon. This natural carbon source drives reductive dehalogenation (i.e., the primary substrate for microorganism growth is native organic carbon). When evaluating natural attenuation of a Type 2 chlorinated solvent plume, the same questions as those posed in the description of Type 1 behavior must be answered. Type 2 behavior generally results in slower biodegradation of the highly chlorinated solvents than Type 1 behavior, but under the right conditions (e.g., areas with high natural organic carbon contents), this type of behavior also can result in rapid degradation of CAH compounds.

4.1.3.3 Type 3 Behavior

Type 3 behavior dominates in areas characterized by low concentrations of native and/or anthropogenic carbon, and concentrations of DO that are greater than 1.0 mg/L. Under these aerobic conditions reductive dehalogenation will not occur. Thus there is little or no removal of PCE and TCE. Biodegradation may proceed via the much slower process of cometabolism, but will be limited by the low concentrations of native or anthropogenic carbon. The most significant natural attenuation mechanisms for CAHs will be advection, dispersion, and sorption. However, VC can be rapidly oxidized under these conditions, DCE may be oxidized, and CBs may be oxidized.

4.1.3.4 Mixed Behavior

A single chlorinated solvent plume can exhibit all three types of behavior in different portions of the plume. This mixed behavior can be beneficial for natural biodegradation of CAH plumes. For example, Wiedemeier *et al.* (1996b) describe a CAH plume at Plattsburgh AFB, New York, that exhibits Type 1 behavior in the source area and Type 3 behavior downgradient along the contaminant flowpath from the source. The best scenario involves a plume in which PCE, TCE, and DCE are reductively dehalogenated (Type 1 or Type 2 behavior), then VC is oxidized (Type 3 behavior), either aerobically or anaerobically (via iron reduction). VC is oxidized to carbon dioxide in this type of plume and does not accumulate. The following sequence of reactions occurs in a plume that exhibits mixed behavior:

$$\text{PCE} \rightarrow \text{TCE} \rightarrow \text{DCE} \rightarrow \text{VC} \rightarrow \text{Carbon Dioxide}$$

In general, the TCE, DCE, and VC may attenuate at approximately the same rate, and the reductive dehalogenation reactions may be confused with simple dilution. Note that no ethene is produced, and VC is removed from the system much faster under oxidizing conditions than under VC-reducing conditions.

A less desirable scenario, but one in which all contaminants may be entirely biodegraded, involves a plume in which all CAHs are reductively dehalogenated via Type 1 or Type 2 behavior. VC is reduced to ethene, which may be further reduced to ethane or methane. The following sequence of reactions occur in this type of plume:

$$\text{PCE} \rightarrow \text{TCE} \rightarrow \text{DCE} \rightarrow \text{VC} \rightarrow \text{Ethene or Ethane}$$

In a reductive plume, VC degrades more slowly than TCE, and tends to accumulate (Freedman and Gossett, 1989).

4.2 NATURE AND EXTENT OF CONTAMINATION

The first step for evaluating the occurrence and methods of CAH biodegradation is to look at the distribution of contaminants and the biodegradation products of those compounds. At Site LF-03, dissolved groundwater contamination consists of a mixture of compounds, some of which may be electron donors, some of which may be electron acceptors, and some of which may be either donors or acceptors. It is therefore important to evaluate the distribution of all relevant compounds and the spatial relations between their distributions.

Benzene, toluene, and PCE were the only contaminants detected in soils above practical quantitation limits at LF-03. Ethyl-benzene, MTBE, TCE, *cis*-1,2-DCE, *trans*-1,2-DCE, and chloroform were the only contaminants detected in site groundwater at concentrations above the practical quantitation limit. These contaminant and daughter product data are presented in the following sections. Geochemical data are discussed in later sections.

4.2.1 Contaminant Sources

Sources of dissolved groundwater contamination at LF-03 are not clearly defined. It is likely that residues from waste disposal activities at LF-03 have leached into soil and to groundwater and are the primary source of groundwater contamination. However, the exact locations and nature of the releases is not clear from the available data. Residual non-aqueous phase liquid (NAPL) has not been identified during either previous or current subsurface investigations. A detailed summary of past characterization activities is provided in the TS Workplan prepared by Parsons ES (1999).

A total of 23 soil gas samples were collected at LF-03 and analyzed for methane, benzene, VC, TCE, *trans*-1,2-DCE, and *cis*-1,2-DCE. Methane was detected in three soil gas samples at concentrations ranging from 1.6 to 3.2 parts per million by volume (ppmv). Benzene was detected at one sampling location within the boundary of LF-03 at a concentration of 0.8 micrograms per liter (µg/L). Neither TCE nor *trans*-1,2-DCE were detected in any of 23 soil gas samples collected. VC was detected in 7 of the 23 soil gas samples at concentrations ranging from 0.5 to 15.4 µg/L, with the highest detections occurring within the boundaries of the landfill. *Cis*-1,2-DCE was detected in 6 of the 23 soil gas samples at concentrations ranging from 0.7 to 8.3 µg/L. Five of the 6 *cis*-1,2-DCE detections occurred within the boundaries of LF-03.

In 1993, soil samples were collected at 10 locations located within and cross-gradient from the LF-03 boundary to gather data on the nature and extent of surface and near-surface contamination (refer to Figure 1.3 for sampling locations). These soil samples were analyzed for VOCs, semivolatile organic compounds (SVOCs), organochlorine pesticides, polychlorinated biphenyls (PCBs), and total metals. No VOCs were detected in soil samples collected from the 1.5- to 2.0-foot depth interval. The only SVOCs detected were measured at SB-LF3-07 at the 0- to 0.5-foot depth interval. Eleven SVOCs were detected in a soil sample collected at sampling location SB-LF3-07 at a combined

total concentration of 28.5 milligrams per kilogram (mg/kg). All the detected SVOCs are common components of asphalts and motor oils (Verschueren, 1983). Low concentrations of organochlorine pesticides, PCBs, and metals were detected in soil samples collected at LF-03, but are not addressed within the scope of this TS.

Between July and November 1993, groundwater samples were collected from 49 temporary test wells and 27 permanent wells (Figure 1.3). Analytical results for selected VOCs for these sampling events are summarized in Table 4.1. Benzene was detected below its federal MCL of 5 µg/L in 4 of the 76 collected groundwater samples at concentrations ranging from 0.2 to 0.9 µg/L. TCE was detected above its federal MCL of 5 µg/L in 12 of the 76 collected groundwater samples. A maximum concentration of 113 µg/L of TCE was detected at test well HP-18, located south of the LF-03 boundary. The areal distribution of the TCE plume in 1993 is presented on Figure 4.3. TCE appears to extend from the landfill toward the northeast, along the regional groundwater flow path. The northeastern edge of the TCE plume extends to HP-28, where TCE was not detected. The areal distribution of *cis*-1,2-DCE in groundwater is similar to that of TCE, with the maximum detection of 93 µg/L occurring at test well HP-18 (Figure 4.4). Cis-1,2-DCE also is migrating with groundwater toward the northeast with the maximum extent of the plume about 150 feet downgradient from well 211. *Trans*-1,2-DCE was detected in 7 of the 76 collected groundwater samples. The maximum detection of *trans*-1,2-DCE (16 µg/L) corresponded with maximum detections of TCE and *cis*-1,2-DCE. VC was detected at concentrations ranging from 0.4 to 51 µg/L. PCE, 1,1-DCE, and methylene chloride were not detected.

In April 1994, 12 groundwater samples were collected from the off-Base Nob Hill area domestic wells, located east of (downgradient from) LF-03 (see Figure 1.2). PCE was the only contaminant detected above its federal MCL of 5 µg/L at concentration of 11 µg/L in well 1818 Fairview. It also was detected in another well at a concentration of 1.8 µg/L. TCE was detected in 3 of the 12 off-Base groundwater samples at concentrations ranging from 0.22 to 2.2 µg/L. *Cis*-1,2-DCE, *trans*-1,2-DCE, and VC were not detected in any of the monitoring wells sampled in the Nob Hill development.

In September 1995, groundwater samples were collected at 9 newly installed monitoring wells and three existing monitoring wells to determine the vertical extent of TCE contamination at LF-03 (Figure 4.5). Analytical results suggest that TCE contamination does not extend into the deep screened interval of monitoring wells 209D or 210D (URS Greiner, 1997). In addition, TCE has not been identified within or below the intermediate depth screened interval of monitoring well 199M1.

4.2.2 Total Organic Carbon in Soil

TOC concentrations are used to estimate the amount of organic matter sorbed to soil particles or trapped in the interstitial passages of a soil matrix. The TOC concentration in

TABLE 4.1
SUMMARY OF HISTORICAL GROUNDWATER ANALYTICAL DATA
SITE LF-03 MNA TS
F.E. WARREN AFB, WYOMING

Sample Identification	Date Sampled	Benzene (µg/L)[a]	Toluene (µg/L)	Ethylbenzene (µg/L)	Total Xylenes (µg/L)	Total BTEX (µg/L)	Gasoline Range Organics (µg/L)	Trichloroethene (µg/L)	Tetrachloroethene (µg/L)	1,1-Dichloroethene (µg/L)	*cis*-1,2-Dichloroethene (µg/L)	*trans*-1,2-Dichloroethene (µg/L)	Methylene Chloride (µg/L)	Vinyl Chloride (µg/L)	bis(2-ethylhexyl)phthalate (µg/L)	Chloride (mg/L)[a]	Nitrate as nitrogen (mg/L)	Sulfate (mg/L)
Federal MCL[b]		5	1,000	700	10,000	--[c]	--	5	5	7	70	100	5	2.0	4	--	--	--
On-Base Monitoring Wells																		
61	Jul/Oct-93	ND[d]	--	--	--	--	--	ND	--	--	ND	ND	--	0.3	ND	42.0	5.8 JTL	75.2
62	Jul/Oct-93	ND	--	--	--	--	--	20.0	--	--	12.2	ND	--	ND	ND	33.1	10.9 JT	54.6
64	Jul/Oct-93	ND	--	--	--	--	--	ND	--	--	ND	ND	--	ND	ND	24.1	6.9	60.9
137	Jul/Oct-93	ND	--	--	--	--	--	ND	--	--	ND	ND	--	ND	ND	22.6	4.6	26.3
138	Jul/Oct-93	ND	--	--	--	--	--	ND	--	--	ND	ND	--	ND	ND	7.2	3.5 JT	14.4
147	Jul/Oct-93	ND	ND	ND	ND	ND	--	15	ND	ND	8.2	ND	ND	ND	120 JP	29.4	9.6 JT	42.2
196	Jul/Oct-93	ND	ND	ND	ND	ND	--	ND	ND	ND	ND	ND	ND	0.6	ND	2.9	1.1 JTL	10.4
196A	Jul/Oct-93	ND	ND	ND	ND	ND	--	ND	ND	ND	ND	ND	ND	0.3	ND	34.7	4.5	24.2
197	Jul/Nov-93	ND	ND	ND	ND	ND	--	ND	ND	ND	ND	ND	ND	ND	ND	20.3	5.4	32.5
198	Jul/Oct-93	ND	ND	ND	ND	ND	--	ND	ND	ND	ND	ND	ND	ND	ND	19.0	6.0	24.4
199	Jul/Oct-93	ND	ND	ND	ND	ND	--	1.2	ND	ND	ND	ND	ND	ND	ND	46.3	3.6	45.6
	Sep-95	ND	ND	ND	ND	ND	ND	2.4	ND	ND	ND	ND	ND	ND	ND	81.6	3.0	58.8
199M1	Sep-95	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	1.8	ND (0.5)	8.8
199D	Sep-95	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	0.26 RV	ND	ND	1.6	ND (0.5)	7.6
201	Jul/Oct-93	ND	ND	ND	ND	ND	--	1.3	ND	ND	ND	ND	ND	ND	ND	85.9	21.0	152.0
	Apr-94	ND	ND	ND	ND	ND	ND	1.3	ND	ND	ND	ND	ND	ND	ND	87.1	22.2	154.0
203	Jul/Oct-93	ND	ND	ND	ND	ND	--	8.8	ND	ND	ND	ND	ND	ND	ND	50.9	7.8	52.8
	Apr-94	ND	ND	ND	ND	ND	ND	8.7	ND	ND	1.4	ND	ND	ND	ND	53.5	8.8 JTL	52.9
206	Jul/Oct-93	ND	ND	ND	ND	ND	--	6.4	ND	ND	1.0	ND	ND	ND	ND	32.6	6.6	39.1
	Apr-94	ND	ND	ND	ND	ND	ND	4.6	ND	ND	0.69 JY	ND	ND	ND	ND UJS	36.2	6.7	41.6
207	Jul/Oct-93	ND	ND	ND	ND	ND	--	11	ND	ND	5.0	ND	ND	ND	ND UJS	51.7	14.4	97.0 JS
208	Jul/Oct-93	ND	ND	ND	ND	ND	--	20	ND	ND	16	ND	ND	ND	ND	68.8	19.6	158.0
209	Jul/Nov-93	ND	ND	ND	ND	ND	--	34.0	ND	ND	28	1.4	ND	ND	ND	46.6	12.0	64.8
	Sep-95	ND	ND	ND	ND	ND	12 RE	24.0	ND	ND	18	ND	0.25 RV	ND	19.0	26.9	10.0	62.7
209M1	Sep-95	ND	ND	ND	ND	ND	ND	72.0	ND	ND	40	0.91 JY	0.70 BM	ND	ND	63.8	20.3	118.0
209D	Sep-95	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	4.6	1.8	10.8
210	Jul/Oct-93	ND	ND	ND	ND	ND	--	44	ND	ND	24	ND	ND	0.9	ND	33.4	13.4	54.7
	Apr-94	ND	ND	ND	ND	ND	ND	37	ND	ND	20	0.49 JY	ND	ND	ND	33.7	13.8	56.3
	Sep-95	ND	ND	ND	ND	ND	14.0	31	ND	ND	17	0.58 JY	0.41 RV	ND	51.0	34.0	12.3	54.6
210M1	Sep-95	ND	ND	ND	ND	ND	7.5 JY	20	ND	ND	6	ND	0.38 RV	ND	8.7 BE	14.6	1.0	26.1
210D	Sep-95	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	2.9	6.9	16.3
211	Jul/Oct-93	ND	ND	ND	ND	ND	--	19	ND	ND	9.1	ND	ND	0.9	14 BM	38.4	8.7	41.7

TABLE 4.1 (Continued)

SUMMARY OF HISTORICAL GROUNDWATER ANALYTICAL DATA

SITE LF-03 MNA TS

F.E. WARREN AFB, WYOMING

Sample Identification	Date Sampled	Benzene (µg/L)[a]	Toluene (µg/L)	Ethylbenzene (µg/L)	Total Xylenes (µg/L)	Total BTEX (µg/L)	Gasoline Range Organics (µg/L)	Trichloroethene (µg/L)	Tetrachloroethene (µg/L)	1,1-Dichloroethene (µg/L)	*cis*-1,2-Dichloroethene (µg/L)	*trans*-1,2-Dichloroethene (µg/L)	Methylene Chloride (µg/L)	Vinyl Chloride (µg/L)	bis(2-ethylhexyl)phthalate (µg/L)	Chloride (mg/L)[a]	Nitrate as nitrogen (mg/L)	Sulfate (mg/L)
Federal MCL[b]		5	1,000	700	10,000	--[c]	--	5	5	7	70	100	5	2.0	4	--	--	--
229	Jul/Oct-93	ND	ND	ND	ND	ND	--	ND	ND	ND	ND	ND	ND	13.1	ND	72.6	4.5	87.1
230	Jul/Oct-93	ND	ND	ND	ND	ND	--	ND	ND	ND	ND	ND	ND	ND	ND	44.1	5.9	61.3
231	Jul/Nov-93	ND	ND	ND	ND	ND	--	ND	ND	ND	ND	ND	ND	ND	ND	13.8	7.1	36.9
232	Jul/Oct-93	ND	ND	ND	ND	ND	--	ND	ND	ND	ND	ND	ND	ND	ND	77.8	4.5	74.9
233	Jul/Nov-93	ND	ND	ND	ND	ND	--	ND	ND	ND	ND	ND	ND	ND	ND	16.3	4.7	33.4
234	Jul/Oct-93	ND	ND	ND	ND	ND	--	ND	ND	ND	ND	ND	ND	ND	ND	21.4	7.7	23.3
235	Jul/Oct-93	ND	ND	ND	ND	ND	--	ND	ND	ND	ND	ND	ND	ND	ND	36.1	10.4	69.4
	Apr-94	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	31.2	12.4 JTL	67.8
236	Jul/Nov-93	ND	ND	ND	ND	ND	--	ND	ND	ND	ND	ND	ND	ND	ND	322	7.2	176.0
238	May-94	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	82.0	4.6	188.0
239	Sep-95	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	45.5	2.5	29.2
240R	Sep-95	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	1.4 RE	233.0	30.9	224.0
241	Sep-95	ND	ND	ND	ND	ND	ND	0.60 JY	ND	ND	ND	ND	0.27 RV	ND	5.4 RE	117.0	4.9	164.0
Temporary Test Wells																		
HP--01	Jul/Oct-93	ND	--	--	--	--	--	ND	--	--	ND	0.3	--	2.0	--	37.1	5.7	66.8
HP-02	Jul/Oct-93	0.2	--	--	--	0.2	--	ND	--	--	ND	0.3	--	2.8	--	56.9	11.3	144.0
HP-03	Jul/Oct-93	ND	--	--	--	--	--	0.2	--	--	ND	0.4	--	2.5	--	56.1	17.9	146.0
HP-04	Jul/Oct-93	0.2	--	--	--	0.2	--	0.3	--	--	ND	ND	--	7.1	--	7.1	4.0	10.0
HP-05	Jul/Oct-93	ND	--	--	--	--	--	ND	--	--	ND	ND	--	3.6	--	16.6	10.0	31.7
HP-06	Jul/Oct-93	ND	--	--	--	--	--	2.2	--	--	1.1	ND	--	11.0	--	10.7	4.3	50.0
HP-07	Jul/Oct-93	ND	--	--	--	--	--	13.0	--	--	11.0	ND	--	15.0	--	50.7	8.2	41.1
HP-08	Jul/Oct-93	ND	--	--	--	--	--	1.7	--	--	ND	ND	--	1.4	--	21.3	5.1	51.2
HP-09	Jul/Oct-93	ND	--	--	--	--	--	ND	--	--	ND	ND	--	4.2	--	5.6	0.8	35.2
HP-10	Jul/Oct-93	ND	--	--	--	--	--	0.2	--	--	2.5	0.2	--	10.0	--	42.2	4.3	47.3
HP-11	Jul/Oct-93	0.5	ND	ND	ND	0.5		0.9	ND	ND	8.0	0.9	ND	ND	--	24.6	11.0	30.9
HP-12	Jul/Oct-93	ND	--	--	--	--	--	ND	--	--	1.2	ND	--	0.8	--	16.3	4.9	22.4
HP-13	Jul/Oct-93	ND	--	--	--	--	--	ND	--	--	ND	ND	--	0.4	--	34.2	5.7	44.7
HP-14	Jul/Oct-93	ND	--	--	--	--	--	1.1	--	--	ND	ND	--	0.4	--	66.5	3.0	58.4
HP-15	Jul/Oct-93	ND	--	--	--	--	--	0.2	--	--	ND	0.1	--	0.7	--	83.3	6.6	94.3
HP-16	Jul/Oct-93	ND	--	--	--	--	--	0.7	--	--	ND	ND	--	0.4	--	13.2	2.9	18.6
HP-17	Jul/Oct-93	ND	--	--	--	--	--	39.0	--	--	17.0	ND	--	ND	--	27.8	11.0	41.2
HP-18	Jul/Oct-93	ND	--	--	--	--	--	113.0	--	--	93.0	16.0	--	ND	--	75.9	21.8	134.0
HP-19	Jul/Oct-93	ND	--	--	--	--	--	ND	--	--	ND	ND	--	ND	--	9.9	6.2	55.0

TABLE 4.1 (Continued)

SUMMARY OF HISTORICAL GROUNDWATER ANALYTICAL DATA

SITE LF-03 MNA TS

F.E. WARREN AFB, WYOMING

Sample Identification	Date Sampled	Benzene (µg/L)[a]	Toluene (µg/L)	Ethylbenzene (µg/L)	Total Xylenes (µg/L)	Total BTEX (µg/L)	Gasoline Range Organics (µg/L)	Trichloroethene (µg/L)	Tetrachloroethene (µg/L)	1,1-Dichloroethene (µg/L)	*cis*-1,2-Dichloroethene (µg/L)	*trans*-1,2-Dichloroethene (µg/L)	Methylene Chloride (µg/L)	Vinyl Chloride (µg/L)	bis(2-ethylhexyl)phthalate (µg/L)	Chloride (mg/L)[a]	Nitrate as nitrogen (mg/L)	Sulfate (mg/L)
Federal MCL[b]		5	1,000	700	10,000	--[c]	--	5	5	7	70	100	5	2.0	4	--	--	--
HP-20	Jul/Oct-93	ND	--	--	--	--	--	ND	--	--	ND	ND	--	11.0	--	52.6	5.8	61.8
HP-21	Jul/Oct-93	ND	--	--	--	--	--	ND	--	--	ND	ND	--	ND	--	22.3	6.6	30.2
HP-22	Jul/Oct-93	ND	--	--	--	--	--	ND	--	--	ND	ND	--	12.0	--	32.9	5.2	64.8
HP-23	Jul/Oct-93	0.9	--	--	--	0.9	--	0.4	--	--	3.3	ND	--	51.0	--	59.2	ND (0.5)	60.6
HP-24	Jul/Oct-93	ND	--	--	--	--	--	ND	--	--	ND	ND	--	ND	--	34.8	8.8	55.3
HP-25	Jul/Oct-93	ND	--	--	--	--	--	ND	--	--	ND	ND	--	5.1	--	34.3	5.6	44.9
HP-26	Jul/Oct-93	ND	--	--	--	--	--	ND	--	--	ND	ND	--	ND	--	16.2	3.5	21.0
HP-27	Jul/Oct-93	ND	--	--	--	--	--	ND	--	--	ND	ND	--	ND	--	33.8	3.3	35.5
HP-28	Jul/Oct-93	ND	--	--	--	--	--	ND	--	--	ND	ND	--	ND	--	21.2	0.57	43.6
HP-29	Jul/Oct-93	ND	--	--	--	--	--	ND	--	--	ND	ND	--	ND	--	249.0	4.5	74.7
HP-30	Jul/Oct-93	ND	--	--	--	--	--	ND	--	--	ND	ND	--	ND	--	342.0	11.7	170.0
HP-31	Jul/Oct-93	ND	--	--	--	--	--	0.5	--	--	ND	ND	--	ND	--	95.3	25.7	165
HP-32	Jul/Oct-93	ND	--	--	--	--	--	3.8	--	--	ND	ND	--	ND	--	39.6	7.2	41.2
HP-33	Jul/Oct-93	ND	--	--	--	--	--	2.4	--	--	ND	ND	--	ND	--	35.1	6.3	37.6
HP-34	Jul/Oct-93	ND	--	--	--	--	--	ND	--	--	ND	ND	--	ND	--	43.6	7.9	51.6
HP-35	Jul/Oct-93	ND	--	--	--	--	--	ND	--	--	ND	ND	--	ND	--	36.9	8.2	51.5
HP-36	Jul/Oct-93	ND	--	--	--	--	--	ND	--	--	ND	ND	--	ND	--	39.7	9.2	56.8
HP-37	Jul/Oct-93	ND	--	--	--	--	--	ND	--	--	ND	ND	--	1.3	--	20.1	5.3	48.4
HP-38	Jul/Oct-93	ND	--	--	--	--	--	ND	--	--	3.3	ND	--	38.0	--	33	2.5	24.3
HP-39	Jul/Oct-93	ND	--	--	--	--	--	ND	--	--	ND	ND	--	ND	--	39.2	7.4	66.9
HP-40	Jul/Oct-93	ND	--	--	--	--	--	ND	--	--	ND	ND	--	ND	--	25.9	3.6	47.2
HP-41	Jul/Oct-93	ND	--	--	--	--	--	2.2	--	--	ND	ND	--	ND	--	45.8	5.1	70.1
HP-42	Jul/Oct-93	ND	--	--	--	--	--	ND	--	--	ND	ND	--	ND	--	29.8	12.2	58
HP-43	Jul/Oct-93	ND	--	--	--	--	--	ND	--	--	ND	ND	--	0.9	--	50.7	11.5	77.2
HP-44	Jul/Oct-93	ND	--	--	--	--	--	ND	--	--	ND	ND	--	ND	--	105	20	200
HP-45	Jul/Oct-93	ND	--	--	--	--	--	ND	--	--	ND	ND	--	ND	--	120	10.9	42.6
HP-46	Jul/Oct-93	ND	--	--	--	--	--	1.2	--	--	ND	ND	--	ND	--	95.1	17.7	172
HP-47	Jul/Oct-93	ND	--	--	--	--	--	ND	--	--	ND	ND	--	5.1	--	24.7	5	54.3
HP-48	Jul/Oct-93	ND	--	--	--	--	--	ND	--	--	ND	ND	--	ND	--	19.7	8.3	24.5
HP-49	Jul/Oct-93	ND	--	--	--	--	--	ND	--	--	ND	ND	--	ND	--	19.8	5.4	23.6
Off-Base Wells																		
2012 CARLIN	Apr-94	ND	ND	ND	ND	ND	37	2.2	ND	ND	ND	ND	ND	ND	ND	45.0	3.3	60.7
2008 CARLIN	Apr-94	ND	ND	ND	ND	ND	ND	0.22 JY	ND	ND	ND	ND	0.20 JY	ND	ND	79.1	1.1	159.0

TABLE 4.1 (Continued)

SUMMARY OF HISTORICAL GROUNDWATER ANALYTICAL DATA

SITE LF-03 MNA TS

F.E. WARREN AFB, WYOMING

Sample Identification	Date Sampled	Benzene (µg/L)[a]	Toluene (µg/L)	Ethylbenzene (µg/L)	Total Xylenes (µg/L)	Total BTEX (µg/L)	Gasoline Range Organics (µg/L)	Trichloroethene (µg/L)	Tetrachloroethene (µg/L)	1,1-Dichloroethene (µg/L)	*cis*-1,2-Dichloroethene (µg/L)	*trans*-1,2-Dichloroethene (µg/L)	Methylene Chloride (µg/L)	Vinyl Chloride (µg/L)	bis(2-ethylhexyl)phthalate (µg/L)	Chloride (mg/L)[a]	Nitrate as nitrogen (mg/L)	Sulfate (mg/L)
Federal MCL[b]		5	1,000	700	10,000	--[c]	--	5	5	7	70	100	5	2.0	4	--	--	--
1929 CARLIN	Apr-94	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	1.8	0.9	6.5
1906 CARLIN	Apr-94	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	0.43 JY	ND	ND	--	--	--
1902 CARLIN	Apr-94	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	28.6	13.0	73.3
4209 STATE	Apr-94	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	--	--	--
4203 STATE	Apr-94	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	128.0	36.9 JTL	173.0
4106 STATE	Apr-94	ND	ND	ND	ND	ND	ND	ND	1.8	0.22 JY	ND	ND	ND	ND	ND	121.0	17.5	90.9
1818 FAIRVIEW	Apr-94	ND	ND	ND	ND	ND	ND	0.49 JY	11	2	ND	ND	ND	ND	ND	147.0	35.7	127.0
4106 OLD HAPPY JACK	Apr-94	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	28.4	10.4 JTL	14.9
4038 OLD HAPPY JACK	Apr-94	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	2.4	0.9	9.1
3909 OLD HAPPY JACK	Apr-94	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	9.4	2.5 JTL	10.4

[a] Units: µg/L = micrograms per liter, mg/L = milligrams per liter.

[b] MCL = Maximum contaminant level for drinking water as determined by the USEPA (USEPA , 1996)

[c] -- = Not available or not analyzed.

[d] ND = Not detected, Parentheses ( ) enclose the reporting limit for ND values.

Data qualifiers:

BE = Analysis is considered as not reliable because analyte concentration is less than or equal to five times the concentration of the associated equipment blank but greater than the concentration of the associated equipment blank.

BM = Analysis is considered as not reliable because analyte concentration is less than or equal to five times the concentration of the associated method blank but greater than the concentration of the associated method blank.

JP = Analysis is considered an estimated value because of problems during collection, transportation, storage, or analysis of the sample.

JTL = Analysis is considered an estimated value and biased low because extraction or analysis holding-time limits were substantially exceeded.

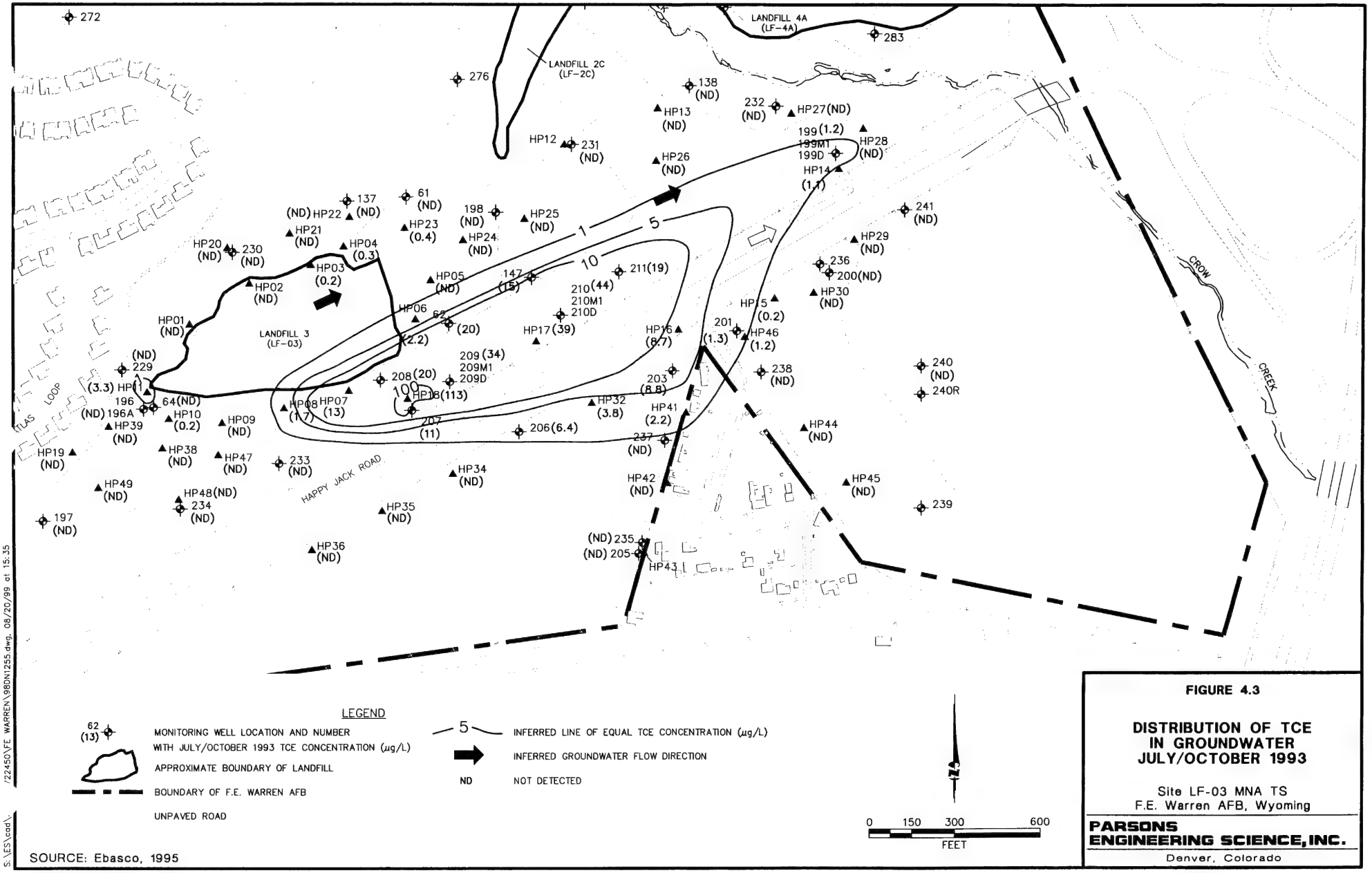
JY = Analysis is considered an estimated value because reported concentration was less than the lowest calibration standard or reporting limit.

RE = Analysis is considered conditionally rejected because analyte concentration was less than or equal to concentration of associated equipment blank.

RM = Analysis is considered conditionally rejected because analyte concentration was less than or equal to concentration of associated method blank.

RV = Analysis is considered conditionally rejected because analyte concentration was less than or equal to concentration of associated trip blank.

UJS = Analysis is considered questionable because the percent recoveries or relative-percent-difference value of associated matrix-spike sample were less than or greater than the quality-control limits.



LEGEND

62 (13) — MONITORING WELL LOCATION AND NUMBER WITH JULY/OCTOBER 1993 TCE CONCENTRATION (µg/L)

APPROXIMATE BOUNDARY OF LANDFILL

BOUNDARY OF F.E. WARREN AFB

UNPAVED ROAD

5 — INFERRED LINE OF EQUAL TCE CONCENTRATION (µg/L)

INFERRED GROUNDWATER FLOW DIRECTION

ND — NOT DETECTED

SOURCE: Ebasco, 1995

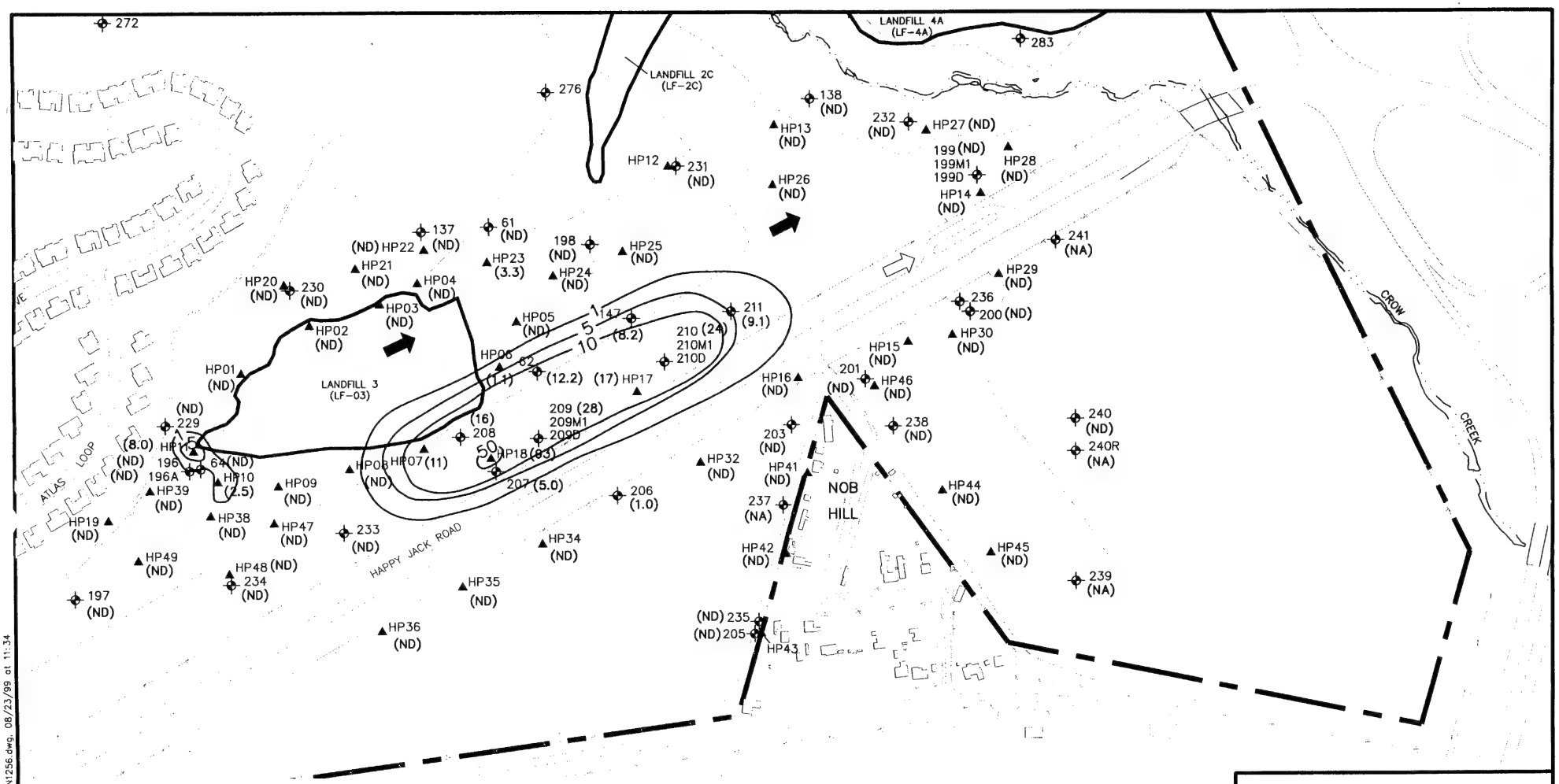
FIGURE 4.3

DISTRIBUTION OF TCE IN GROUNDWATER JULY/OCTOBER 1993

Site LF-03 MNA TS
F.E. Warren AFB, Wyoming

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

S:\ES\cad\...\22450\FE WARREN\98DN1255.dwg, 08/20/99 at 15:35



SOURCE: Ebasco, 1995

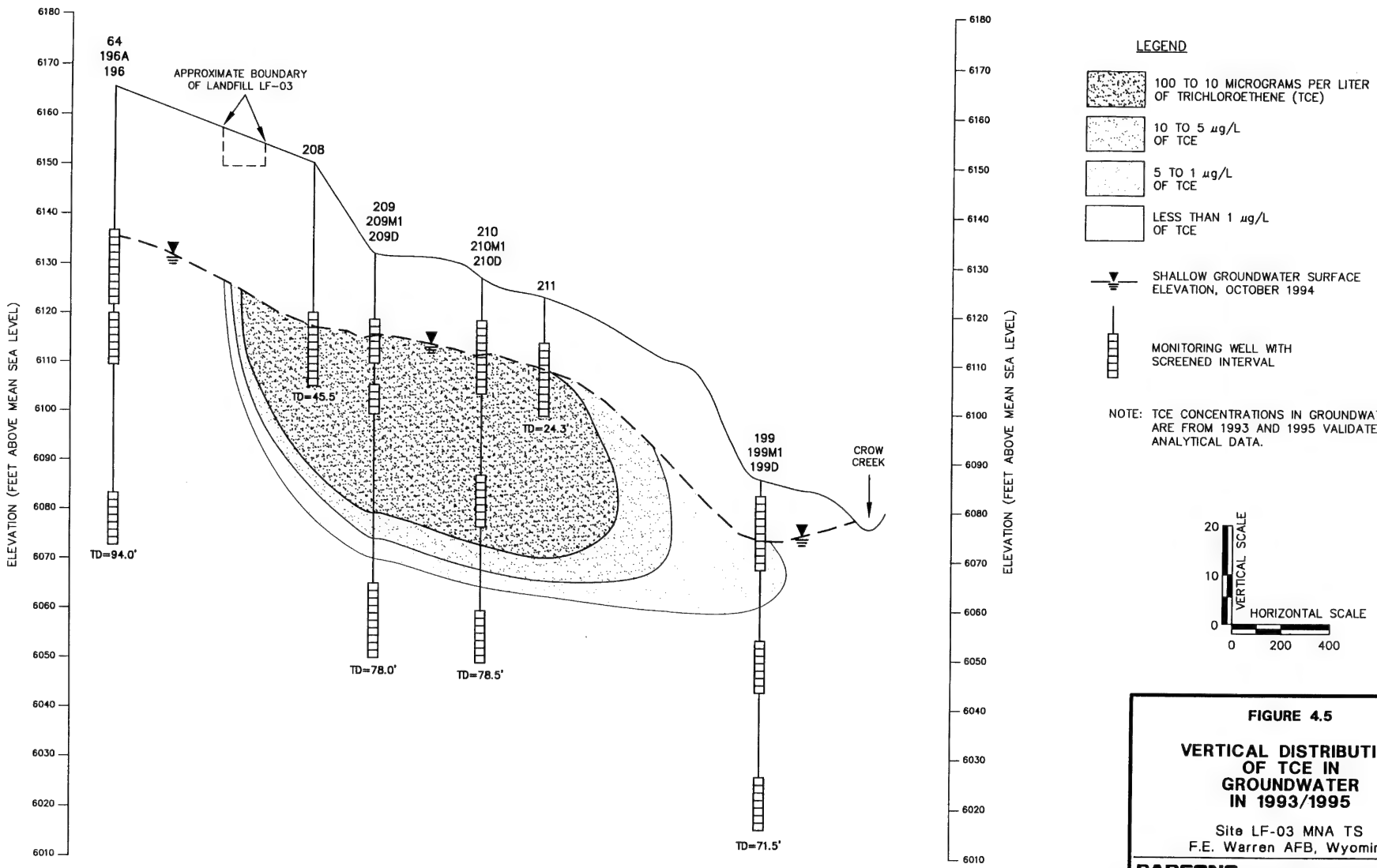
FIGURE 4.4

DISTRIBUTION OF CIS-1,2-DCE IN GROUNDWATER JULY/OCTOBER 1993

Site LF-03 MNA TS
F.E. Warren AFB, Wyoming

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

S:\ES\cad\722450\FE WARREN\98DN1256.dwg, 08/23/99 at 11:34



SOURCE: URS GREINER, 1997

FIGURE 4.5

VERTICAL DISTRIBUTION OF TCE IN GROUNDWATER IN 1993/1995

Site LF-03 MNA TS
F.E. Warren AFB, Wyoming

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

S:\ES\co ...\722450\FE WARREN\99dn0033.dwg, 08/20/99 at 13:31

the saturated zone is an important parameter used to estimate the amount of contaminant that could potentially sorb to organic carbon in the aquifer matrix. Sorption results in retardation of the contaminant plume relative to the average advective groundwater velocity. In addition, TOC can be used as a gross indicator of organic compounds that are available as a source of carbon and electron donors (or substrate) for a microbial population.

Soil TOC concentrations were measured in 21 samples collected from 7 borehole locations in 1999 (Table 4.2). All samples were collected from below the water table. Soil TOC concentrations ranged from 0.012 to 0.049 percent, and averaged 0.027 percent. For most of the CAHs detected at LF-03, contaminant retardation due to sorption is significant when TOC concentrations are greater than approximately 0.01 percent. Because TOC concentrations at LF-03 are greater than 0.01 percent, sorption of dissolved CAHs onto organic carbon may play some role in contaminant retardation at LF-03.

4.2.3 Fuel Hydrocarbons in Groundwater

Total BTEX was detected in 2 of 34 groundwater samples collected from the aquifer at LF-03. Results for fuel hydrocarbon analyses performed on samples collected in May 1999 are presented in Table 4.3. Total BTEX was detected at concentrations of 1.2 and 2.1 µg/L for wells 238 and PES-4D, respectively. Ethyl-benzene was the only BTEX compound detected above its practical quantitation limit at these two locations. This single detection is well below the federal MCL of 700 µg/L. Because the detected fuel hydrocarbons at the site are at such low concentrations, natural attenuation of these compounds is not further analyzed.

4.2.4 Dissolved Chlorinated Ethenes

Chlorinated ethenes detected in groundwater at LF-03 in 1999 during the TS include TCE and DCE. Data for chlorinated ethenes and other chlorinated compounds are presented in Table 4.4. Distributions of TCE and cis-1,2-DCE are shown on Figures 4.6 and 4.7, respectively.

TCE was detected in 16 of the 34 groundwater samples collected at LF-03 in May 1999 (Figure 4.6). TCE concentrations detected in the upper portion of the aquifer ranged from 1.1 µg/L at well 238 to 93 µg/L at well 209. At the later location, TCE also was detected in the intermediate zone of the aquifer at a concentration of 76.2 µg/L (well 209M1). However, TCE was not detected in any of the monitoring wells screened in the deep portion of the aquifer. Of these detections, 12 measured concentrations of TCE exceeded the federal MCL of 5 µg/L.

The 1999 areal distribution of TCE (Figure 4.6) has remained roughly the same as the 1993 TCE plume distribution (Figure 4.3). The area of the highest TCE concentration is presently centered around well 209, downgradient from HP-18, the highest TCE detection in 1993. The highest concentration of TCE detected in 1993 was 113 µg/L; the highest concentration of TCE detected in 1999 was 93 µg/L. Although TCE concentrations do

TABLE 4.2
TOTAL ORGANIC CARBON IN SOIL
JULY 1997
SITE LF-03 MNA TS
F.E. WARREN AFB, WYOMING

Sample Location	Sample Date	Sample Depth (feet bgs)[a/]	Sample Replicate	Total Organic Carbon (percent)
PES-1S	May-99	32.0' - 33.0'	Replicate 1	0.049
PES-1S	May-99	32.0' - 33.0'	Replicate 2	0.034
PES-1S	May-99	32.0' - 33.0'	Replicate 3	0.032
			Mean TOC:	**0.038**
PES-2D	May-99	22.0' - 23.0'	Replicate 1	0.032
PES-2D	May-99	22.0' - 23.0'	Replicate 2	0.045
PES-2D	May-99	22.0' - 23.0'	Replicate 3	0.030
			Mean TOC:	**0.036**
PES-3D	May-99	14.5' - 15.5'	Replicate 1	0.016
PES-3D	May-99	14.5' - 15.5'	Replicate 2	0.022
PES-3D	May-99	14.5' - 15.5'	Replicate 3	0.020
			Mean TOC:	**0.019**
PES-4D	May-99	20.0' - 22.0'	Replicate 1	0.025
PES-4D	May-99	20.0' - 22.0'	Replicate 2	0.028
PES-4D	May-99	20.0' - 22.0'	Replicate 3	0.030
			Mean TOC:	**0.028**
PES-5D	May-99	15.0' - 16.0'	Replicate 1	0.020
PES-5D	May-99	15.0' - 16.0'	Replicate 2	0.021
PES-5D	May-99	15.0' - 16.0'	Replicate 3	0.012
			Mean TOC:	**0.018**
PES-6S	May-99	24.5' - 25.5'	Replicate 1	0.028
PES-6S	May-99	24.5' - 25.5'	Replicate 2	0.033
PES-6S	May-99	24.5' - 25.5'	Replicate 3	0.021
			Mean TOC:	**0.027**
PES-6D	May-99	29.5' - 30.0'	Replicate 1	0.026
PES-6D	May-99	29.5' - 30.0'	Replicate 2	0.030
PES-6D	May-99	29.5' - 30.0'	Replicate 3	0.020
			Mean TOC:	**0.025**
			Average of Mean TOC Values:	**0.027**

[a/] feet bgs = feet below ground surface.

TABLE 4.3

FUEL HYDROCARBONS AND MTBE[a/] IN GROUNDWATER

MAY 1999

SITE LF-03 MNA TS

F.E. WARREN AFB, WYOMING

Sample Location	Sample Date	MTBE (µg/L)[c/]	Benzene (µg/L)	Toluene (µg/L)	Ethyl-benzene (µg/L)	p-Xylene (µg/L)	m-Xylene (µg/L)	o-Xylene (µg/L)	Total Xylenes (µg/L)	Total BTEX[b/] (µg/L)
MCL[d/]		—[e/]	5	1,000	700	—	—	—	10,000	—
62	May-99	ND[f/]	< 1[g/]	< 1	ND	ND	< 1	< 1	< 1	ND
64	May-99	ND	ND	< 1	ND	ND	< 1	ND	< 1	ND
147	May-99	ND	ND	< 1	< 1	< 1	ND	ND	< 1	ND
196	May-99	ND	ND	< 1	< 1	ND	< 1	ND	< 1	ND
196A	May-99	ND	ND	< 1	ND	ND	< 1	ND	< 1	ND
197	May-99	ND	ND	ND	ND	ND	ND	< 1	< 1	ND
198	May-99	ND	ND	< 1	ND	ND	ND	< 1	< 1	ND
198 DUP[h/]	May-99	ND	ND	< 1	ND	ND	ND	ND	ND	ND
199D	May-99	ND	ND	< 1	ND	ND	ND	ND	ND	ND
199M	May-99	< 1	ND	ND	ND	< 1	ND	ND	< 1	ND
199S	May-99	ND	ND	< 1	ND	< 1	< 1	ND	< 1	ND
201	May-99	ND	ND	< 1	< 1	ND	< 1	ND	< 1	ND
203	May-99	ND	ND	< 1	ND	ND	< 1	ND	< 1	ND
206	May-99	ND	ND	ND	ND	ND	ND	ND	ND	ND
207	May-99	ND	ND	ND	ND	ND	ND	ND	ND	ND
208	May-99	ND	ND	ND	ND	ND	ND	ND	ND	ND
209	May-99	ND	ND	< 1	ND	ND	ND	ND	ND	ND
209D	May-99	ND	ND	ND	ND	ND	ND	ND	ND	ND
[illegible]09D DUP	May-99	ND	ND	ND	ND	ND	ND	ND	ND	ND
[illegible]09M1	May-99	ND	ND	ND	ND	ND	ND	ND	ND	ND
210	May-99	ND	ND	ND	ND	ND	ND	ND	ND	ND
210D	May-99	ND	ND	ND	ND	ND	ND	ND	ND	ND
210M1	May-99	ND	ND	ND	ND	ND	ND	ND	ND	ND
211	May-99	ND	ND	ND	ND	ND	ND	ND	ND	ND
232	May-99	ND	ND	ND	ND	ND	ND	ND	ND	ND
233	May-99	ND	ND	< 1	ND	ND	ND	ND	ND	ND
236	May-99	< 1	< 1	< 1	ND	< 1	< 1	ND	< 1	ND
237	May-99	ND	ND	ND	< 1	< 1	< 1	< 1	< 1	ND
238	May-99	ND	ND	< 1	1.2	< 1	< 1	ND	< 1	1.2
PES-1S	May-99	ND	ND	ND	ND	< 1	ND	ND	< 1	ND
PES-1S DUP	May-99	ND	ND	ND	ND	ND	ND	ND	ND	ND
PES-2D	May-99	ND	ND	ND	ND	ND	ND	< 1	< 1	ND
PES-3D	May-99	1.4	ND	ND	ND	< 1	< 1	ND	< 1	ND
PES-4D	May-99	< 1	ND	ND	2.1	ND	< 1	< 1	< 1	2.1
PES-5D	May-99	ND	ND	ND	ND	ND	ND	ND	ND	ND
PES-6S	May-99	ND	ND	ND	ND	< 1	< 1	ND	< 1	ND
PES-6D	May-99	ND	ND	< 1	< 1	< 1	ND	ND	< 1	ND

[a/] MTBE = Methyl tert-butyl ether.

[b/] BTEX = Benzene, Toluene, Ethylbenzene, and p-, m-, and o-Xylene.

[c/] µg/L = micrograms per liter.

[d/] MCL = Maximum Contaminant Level, USEPA Primary Drinking Water Regulations, May 14, 1996.

[e/] — = No standard listed.

[f/] [illegible]not detected.

[g/] [illegible] = less than listed laboratory-reported practical quantitation limit.

[h/] Duplicate of preceding sample.

TABLE 4.4
CHLORINATED ALIPHATIC HYDROCARBONS IN GROUNDWATER
MAY 1999
SITE LF-03 MNA TS
F.E. WARREN AFB, WYOMING

Sample Location	Sample Date	PCE[a] (µg/L)	TCE[a] (µg/L)	1,1-DCE[a] (µg/L)	*cis*-1,2-DCE (µg/L)	*trans*-1,2-DCE (µg/L)	VC[a] (µg/L)[b]	1,1,1-TCA[a] (µg/L)	1,1-DCA[a] (µg/L)	1,2-DCA (µg/L)	Carbon Tetrachloride (µg/L)	Chloroform (µg/L)
MCL[c]		5	5	7	70	100	2	200	—[d]	5	5	—
62	May-99	ND	< 1[e]	ND	< 1	ND	ND[f]	ND	ND	ND	ND	< 1
64	May-99	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	2.3
147	May-99	ND	10.3	ND	6.1	ND	ND	ND	ND	ND	ND	< 1
147 DUP[g]	May-99	ND	10.5	ND	5.6	ND	ND	ND	ND	ND	ND	< 1
196	May-99	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
196A	May-99	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	1.0
197	May-99	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
198	May-99	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	< 1
199	May-99	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
199M1	May-99	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
199D	May-99	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
201	May-99	ND	< 1	ND	ND	ND	ND	ND	ND	ND	ND	ND
203	May-99	ND	12.8	ND	5.1	ND	ND	ND	ND	ND	ND	ND
206	May-99	ND	2.6	ND	1.2	ND	ND	ND	ND	ND	ND	ND
207	May-99	ND	33.1	ND	34.9	1.7	ND	ND	ND	ND	ND	< 1
208	May-99	ND	23.0	ND	22.8	< 1	ND	ND	ND	ND	ND	< 1
209	May-99	ND	93.1	ND	129	5.7	ND	ND	ND	ND	ND	< 1
209M1	May-99	ND	76.2	ND	50.0	1.3	ND	ND	ND	ND	ND	< 1
209M1 DUP	May-99	ND	77.9	ND	49.6	1.2	ND	ND	ND	ND	ND	< 1
209D	May-99	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
210	May-99	ND	26.7	ND	15.8	< 1	ND	ND	ND	ND	ND	< 1
210M1	May-99	ND	18.3	ND	6.9	ND	ND	ND	ND	ND	ND	ND
210D	May-99	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

TABLE 4.4 (Continued)
CHLORINATED ALIPHATIC HYDROCARBONS IN GROUNDWATER
MAY 1999
SITE LF-03 MNA TS
F.E. WARREN AFB, WYOMING

Sample Location	Sample Date	PCE[a/] (µg/L)	TCE[a/] (µg/L)	1,1-DCE[a/] (µg/L)	*cis*-1,2-DCE (µg/L)	*trans*-1,2-DCE (µg/L)	VC[a/] (µg/L)[b/]	1,1,1-TCA[a/] (µg/L)	1,1-DCA[a/] (µg/L)	1,2-DCA (µg/L)	Carbon Tetrachloride (µg/L)	Chloroform (µg/L)
MCL[c/]		5	5	7	70	100	2	200	—[d/]	5	5	—
211	May-99	ND	7.5	ND	3.3	ND	ND	ND	ND	ND	ND	< 1
232	May-99	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	< 1
233	May-99	ND	< 1	ND	ND	ND	ND	ND	ND	ND	ND	ND
236	May-99	ND	< 1	ND	ND	ND	ND	ND	ND	ND	ND	ND
237	May-99	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
237 DUP	May-99	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
238	May-99	ND	1.1	ND	ND	ND	ND	ND	ND	ND	ND	2.3
PES-1S	May-99	ND	33.9	ND	31.9	1.6	ND	ND	ND	ND	ND	< 1
PES-2D	May-99	ND	4.3	ND	2.3	ND	ND	ND	ND	ND	ND	1.0
PES-3D	May-99	ND	< 1	ND	ND	ND	ND	ND	ND	ND	ND	ND
PES-4D	May-99	ND	12.3	ND	3.0	ND	ND	ND	ND	ND	ND	ND
PES-5D	May-99	ND	3.3	ND	1.3	ND	ND	ND	ND	ND	ND	ND
PES-6S	May-99	ND	11.0	ND	2.5	ND	ND	ND	ND	ND	ND	ND
PES-6D	May-99	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

[a/] PCE = tetrachloroethene, TCE = trichloroethene, DCE = dichloroethene, VC = vinyl chloride, TCA = trichloroethane, DCA = dichloroethane.

[b/] µg/L = micrograms per liter.

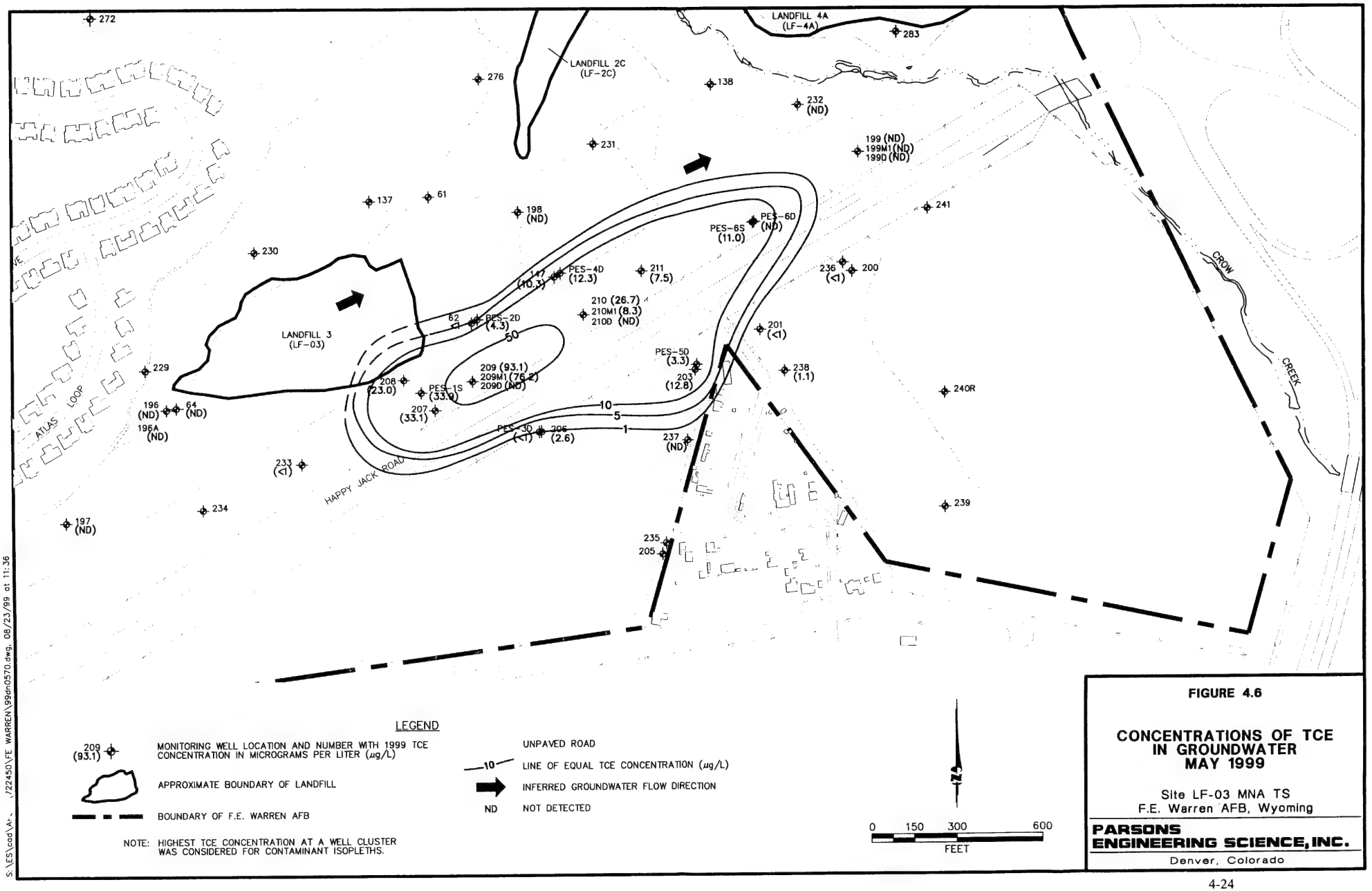
[c/] MCL = Maximum Contaminant Level, USEPA Primary Drinking Water Regulations, May 14, 1996.

[d/] — = No standard listed.

[e/] < 1 = less than listed laboratory-reported practical quantitation limit of 1 µg/L.

[f/] ND = not detected.

[g/] Duplicate of preceding sample.



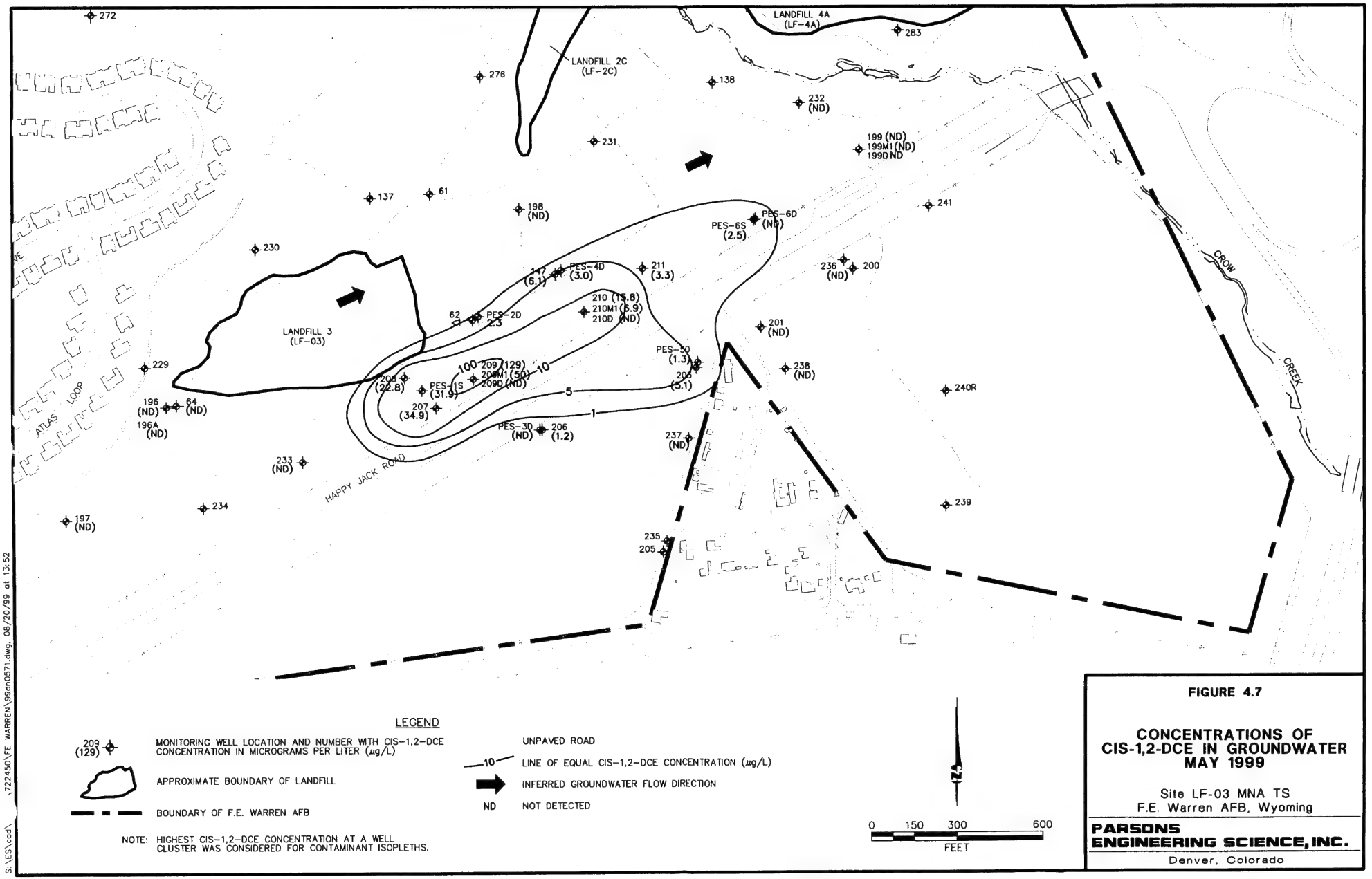
S:\ES\cad\AF~_\72250\FE WARREN\99an0570.dwg, 08/23/99 at 11:36

FIGURE 4.6

CONCENTRATIONS OF TCE IN GROUNDWATER MAY 1999

Site LF-03 MNA TS
F.E. Warren AFB, Wyoming

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado



LEGEND

209 (129) — MONITORING WELL LOCATION AND NUMBER WITH CIS-1,2-DCE CONCENTRATION IN MICROGRAMS PER LITER (µg/L)

APPROXIMATE BOUNDARY OF LANDFILL

BOUNDARY OF F.E. WARREN AFB

UNPAVED ROAD

10 — LINE OF EQUAL CIS-1,2-DCE CONCENTRATION (µg/L)

INFERRED GROUNDWATER FLOW DIRECTION

ND — NOT DETECTED

NOTE: HIGHEST CIS-1,2-DCE CONCENTRATION AT A WELL CLUSTER WAS CONSIDERED FOR CONTAMINANT ISOPLETHS.

FIGURE 4.7

CONCENTRATIONS OF CIS-1,2-DCE IN GROUNDWATER MAY 1999

Site LF-03 MNA TS
F.E. Warren AFB, Wyoming

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

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not appear to be significantly decreasing, the plume also does not appear to be increasing in size (i.e. the plume appears to be stable).

The highest detection in May 1999 of TCE at well 209 suggests that the source of TCE is still associated with the southeastern toe of the LF-03, as was thought in 1995. Although undocumented, the data also suggest that cleaning or dumping operations in the general area of the LF-03 access roads may be potential sources. *cis*-1,2-DCE was detected at several wells (Figure 4.7), with the highest concentration of 129 µg/L detected at well 209. This is the only concentration of *cis*-1,2-DCE to exceed the federal MCL of 70 µg/L. The 3 locations with the highest concentrations of *cis*-1,2-DCE coincide with the highest TCE detections (wells 209, PES-1S, and 207), all of which are in the upper portion of the aquifer. *cis*-1,2-DCE was not detected in any of the intermediate zone monitoring wells.

The 1999 areal distribution of *cis*-1,2-DCE (Figure 4.7) suggests that the plume fringes have expanded beyond those indicated by the 1993 data (Figure 4.4). The area with the highest *cis*-1,2-DCE concentration is presently centered around well 209, downgradient from HP-18, the highest *cis*-1,2-DCE detection in 1993. The highest concentration of *cis*-1,2-DCE detected in 1993 was 93 µg/L; the highest detected concentration of *cis*-1,2-DCE in 1999 was 129 µg/L. In the absence of a known source for this compound, this slight increase may suggest that TCE is biodegrading to *cis*-1,2-DCE.

trans-1,2-DCE was detected at 4 locations at concentrations ranging from 1.3 to 5.7 µg/L. No concentrations exceeded the federal MCL of 100 µg/L. At all wells sampled, *trans*-1,2-DCE was detected at concentrations significantly lower than *cis*-1,2-DCE. This trend would be expected if TCE is being degraded to DCE via reductive dehalogenation. As noted before, under the influence of biodegradation, *cis*-1,2-DCE is a more common daughter product than the other DCE isomers. Furthermore, the *trans* isomer is more common when DCE is used for commercial applications. The presence of *cis*-1,2-DCE is therefore a good indicator that the initial step of TCE reductive dehalogenation is taking place in groundwater at LF-03.

VC was not detected in LF-03 groundwater samples collected in May 1999. In 1993, VC was detected in 29 of 58 groundwater samples at concentrations ranging from 0.3 µg/L to 51 µg/L (Ebasco, 1995). However, VC was not detected in 1994 or 1995 sampling events performed by Ebasco (1995). The overall lack of VC detections, since those initial detections, in groundwater at LF-03 suggests that reductive dehalogenation is generally not proceeding past the initial step that involves the transformation of TCE to DCE.

4.2.5 Ethene in Groundwater

Ethene is the end product of reductive dehalogenation. The lack of VC detections in LF-03 groundwater, described in Section 4.2.4, indicates that ethene (which is produced during the biodegradation of VC) also should be scarce to non-existent in the groundwater. As shown in Table 4.5, ethene was not detected in the groundwater samples collected in May 1999.

TABLE 4.5
GROUNDWATER GEOCHEMICAL DATA
MAY 1999
SITE LF-03 MNA TS
F.E. WARREN AFB, WYOMING

Sample Location	Methane (mg/L) [b/]	Ethene (mg/L)	Ethane (mg/L)	TOC [a/] (mg/L)	Dissolved Oxygen (mg/L)	Nitrate + Nitrite (mg/L)	Ferrous Iron (mg/L)	Sulfide (mg/L)	Sulfate (mg/L)	Total Alkalinity (mg/L)	Carbon Dioxide (mg/L)	Ammonia (mg/L)	Chloride (mg/L)	Redox Potential (mV) [c/]	pH	Temp (°C) [d/]	Conductivity (µs/cm) [e/]
62	< 0.001 [f/]	< 0.003	< 0.002	3.34	2.65	7.65	< 0.1	< 0.1	47.2	160	25	< 0.10	20.8	177	7.45	9.1	556
64	< 0.001	< 0.003	< 0.002	3.98	7.60	6.50	< 0.1	< 0.1	52.4	200	20	< 0.10	24.5	250	7.25	10.9	635
147	< 0.001	< 0.003	< 0.002	5.45	3.80	9.17	< 0.1	<0.1	55.4	200	35	< 0.10	31.4	102	NA [g/]	9.6	704
196	< 0.001	< 0.003	< 0.002	1.93	NA	1.65	< 0.1	< 0.1	16.2	120	15	< 0.10	2.54	NA	NA	NA	NA
196A	< 0.001	< 0.003	< 0.002	39.4	7.50	6.06	< 0.1	<0.1	40.3	140	15	< 0.10	43.2	253	7.29	10.1	570
197	< 0.001	< 0.003	< 0.002	19.1	7.00	4.33	< 0.1	< 0.1	136	220	25	< 0.10	4.08	253	7.47	14.3	839
198	< 0.001	< 0.003	< 0.002	4.18	7.80	7.69	< 0.1	< 0.1	38.3	220	15	< 0.10	26.6	221	7.23	11.7	629
199	0.001	< 0.003	< 0.002	9.79	8.10	5.68	< 0.1	< 0.1	74.3	200	10	< 0.10	30.9	267	7.49	6.8	674
199 DUP	< 0.001	< 0.003	< 0.002	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
199M1	0.001	< 0.003	< 0.002	1.03	6.80	0.83	< 0.1	< 0.1	9.51	140	10	< 0.10	< 0.50	266	7.60	9.1	278
199D	0.001	< 0.003	< 0.002	0.800	6.50	0.82	< 0.1	< 0.1	7.66	120	10	< 0.10	< 0.50	269	7.40	10.5	282
201	< 0.001	< 0.003	< 0.002	14.9	6.80	17.8	< 0.1	< 0.1	487	280	25	< 0.10	299	242	7.16	7.8	290
203	< 0.001	< 0.003	< 0.002	14.7	4.36	8.49	< 0.1	< 0.1	271	200	40	< 0.10	198	106	NA	8.0	1,537
206	< 0.001	< 0.003	< 0.002	5.81	5.40	6.29	< 0.1	< 0.1	84.9	180	20	< 0.10	54.3	126	NA	8.3	697
207	< 0.001	< 0.003	< 0.002	7.31	2.79	0.98	< 0.1	< 0.1	140	200	40	0.99	73.6	202	6.96	10.8	1,130
208	< 0.001	< 0.003	< 0.002	7.93	1.40	19.5	< 0.1	< 0.1	206	240	35	< 0.10	66.6	182	6.83	9.8	1,271
209	< 0.001	< 0.003	< 0.002	7.81	2.08	18.7	< 0.1	< 0.1	145	240	30	< 0.10	68.9	182	6.87	9.2	1,127
209M1	< 0.001	< 0.003	< 0.002	5.52	1.04	17.9	< 0.1	< 0.1	140	200	25	< 0.10	56.9	204	6.98	10.8	1,028
209D	0.001	< 0.003	< 0.002	2.16	2.79	2.00	< 0.1	< 0.1	11.4	180	30	< 0.10	2.13	231	7.53	10.1	312
210	0.001	< 0.003	< 0.002	6.03	1.90	11.3	< 0.1	< 0.1	75.2	180	25	< 0.10	89.9	266	7.12	9.3	969
210M1	< 0.001	< 0.003	< 0.002	5.17	2.67	7.18	< 0.1	< 0.1	25.7	120	25	< 0.10	13.0	214	7.45	11.0	443
210D	< 0.001	< 0.003	< 0.002	4.60	1.35	1.15	< 0.1	< 0.1	18.5	120	20	< 0.10	1.38	276	7.37	10.5	415
210D (DUP)	< 0.001	< 0.003	< 0.002	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
211	< 0.001	< 0.003	< 0.002	6.84	4.33	8.18	< 0.1	NA	47.4	200	25	< 0.10	39.6	120	NA	9.1	694
232	< 0.001	< 0.003	< 0.002	3.24	6.00	5.65	< 0.1	< 0.1	52.6	220	25	< 0.10	43.6	260	7.30	8.8	754
233	< 0.001	< 0.003	< 0.002	4.52	7.30	16.6	< 0.1	< 0.1	78.6	140	15	< 0.10	26.9	250	7.28	11.9	698
236	< 0.001	< 0.003	< 0.002	6.45	5.45	12.3	< 0.1	< 0.1	208	220	25	< 0.10	224	94	NA	9.6	1,598

TABLE 4.5 (Continued)
GROUNDWATER GEOCHEMICAL DATA
MAY 1999
SITE LF-03 MNA TS
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Sample Location	Methane (mg/L) [b/]	Ethene (mg/L)	Ethane (mg/L)	TOC[a/] (mg/L)	Dissolved Oxygen (mg/L)	Nitrate + Nitrite (mg/L)	Ferrous Iron (mg/L)	Sulfide (mg/L)	Sulfate (mg/L)	Total Alkalinity (mg/L)	Carbon Dioxide (mg/L)	Ammonia (mg/L)	Chloride (mg/L)	Redox Potential (mV)[c/]	pH	Temp (°C) [d/]	Conductivity (µs/cm) [e/]
237	0.002	< 0.003	< 0.002	24.6	1.60	4.10	< 0.1	< 0.1	135	240	20	< 0.10	56.8	260	7.40	7.5	955
238	< 0.001	< 0.003	< 0.002	9.42	4.10	7.85	< 0.1	< 0.1	285	300	25	< 0.10	102	251	7.07	8.8	1,470
PES-1S	< 0.001	< 0.003	< 0.002	32.3	1.10	19.3	< 0.1	< 0.1	165	220	40	< 0.10	62.8	59	7.15	10.5	1,178
PES-2D	< 0.001	< 0.003	< 0.002	11.9	1.97	9.25	< 0.1	< 0.1	53.2	240	35	< 0.10	28.8	186	7.25	9.8	825
PES-3D	0.003	0.001	< 0.002	9.72	4.85	3.81	< 0.1	< 0.1	26.3	140	40	< 0.10	14.9	145	NA	10.3	407
PES-3D (DUP)	0.002	< 0.003	< 0.002	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
PES-4D	0.001	< 0.003	< 0.002	31.5	2.03	7.35	< 0.1	< 0.1	27.3	160	15	< 0.10	13.7	140	7.91	11.2	406
PES-5D	0.001	< 0.003	< 0.002	38.0	4.07	4.44	< 0.1	< 0.1	195	140	40	< 0.10	134	121	NA	12.2	1,160
PES-6S	< 0.001	< 0.003	< 0.002	3.18	2.61	6.79	< 0.1	< 0.1	33.4	160	30	< 0.10	24.5	30	7.42	9.1	547
PES-6D	< 0.001	< 0.003	< 0.002	1.56	3.48	1.05	< 0.1	< 0.1	19.6	120	30	< 0.10	1.26	137	8.14	10.6	317
						7.89	#DIV/0!		100.25	187.06					7.32	9.91	
						0.82	0.00		7.66	120.00					6.83		
						19.50	0.00		487.00	300.00					8.14		

[a/] TOC = total organic carbon.

[b/] mg/L = milligrams per liter.

[c/] mV = millivolts.

[d/] °C = degrees Centigrade.

[e/] µs/cm = microsiemens per centimeter.

[f/] Measured value (e.g., <0.001) is less than the estimated reporting limit for this compound.

[g/] NA = not analyzed.

[h/] DUP = Duplicate sample.

4.2.6 Other Dissolved Chlorinated Compounds

Chloroform was the only other chlorinated compound detected in groundwater at LF-03. Chloroform was detected at concentrations of 1.0 µg/L in PES-2D, 2.3 µg/L in well 64, and 2.3 µg/L in well 238. These locations do not coincide with the maximum detected concentrations of TCE and *cis*-1,2-DCE. None of these detected concentrations exceed the federal MCL of 100 µg/L. Chloroform may form as the end product of aerobic degradation of TCE through intermediate byproducts of 2,2,2-trichloroacetaldehyde and 2,2,2-trichloroethanol (Figure 4.2). Therefore, the formation of chloroform in association with the presence of TCE may indicate an aerobic biodegradation pathway from TCE to chloroform.

4.3 ANALYSIS OF CAH BIODEGRADATION

In general, the analytical data suggest that, although only a small fraction of TCE may be transformed to DCE via reductive dehalogenation, and the process is not sufficient to transform the bulk of the parent CAHs and chlorinated daughter products to nonchlorinated end products such as ethene. However, limited oxidation of DCE to carbon dioxide, water, and chlorine ions may be occurring. Therefore, the available information indicates that currently type 3 behavior is prevalent.

In addition to the distribution of contaminants and daughter products, other evidence can be used to support the interpretation that limited biodegradation of chlorinated solvents is occurring. Analysis of temporal changes in contaminant concentrations over time may indicate field-scale contaminant mass loss as a result of biodegradation processes. By comparing concentrations and distributions of electron donors, and byproducts of microbially mediated reactions, types of biodegradation processes operating at a site can be identified. Geochemical parameters, including redox potential, alkalinity, and other changes in groundwater chemistry also can provide supporting evidence and are presented in the following subsections.

4.3.1 Field-Scale Contaminant Mass Loss

Groundwater quality data collected for 2 to 4 sampling events between July/November 1993 and May 1999 from monitoring wells 199, 206, 207, 208, 209, 210 and 211 were reviewed to assess temporal changes in contaminant concentrations over time. Decreasing contaminant concentration over time may indicate natural attenuation processes are at work. In a stable or attenuating contaminant plume, decreasing concentration trends may be used to support loss of contaminant mass through destructive processes such as biodegradation.

4.3.1.1 Chlorinated Ethenes Over Time

Available concentration-versus-time data for chlorinated ethenes in samples from several wells 199, 206, and 210 were examined to reassess whether or not long-term trends in chlorinated ethene concentrations are apparent. Total chlorinated ethene concentrations at wells near the core of the plume (e.g., wells 206, 207, 208, and 209) have gradually increase over time (Figure 4.8). Review of this plot indicates that the

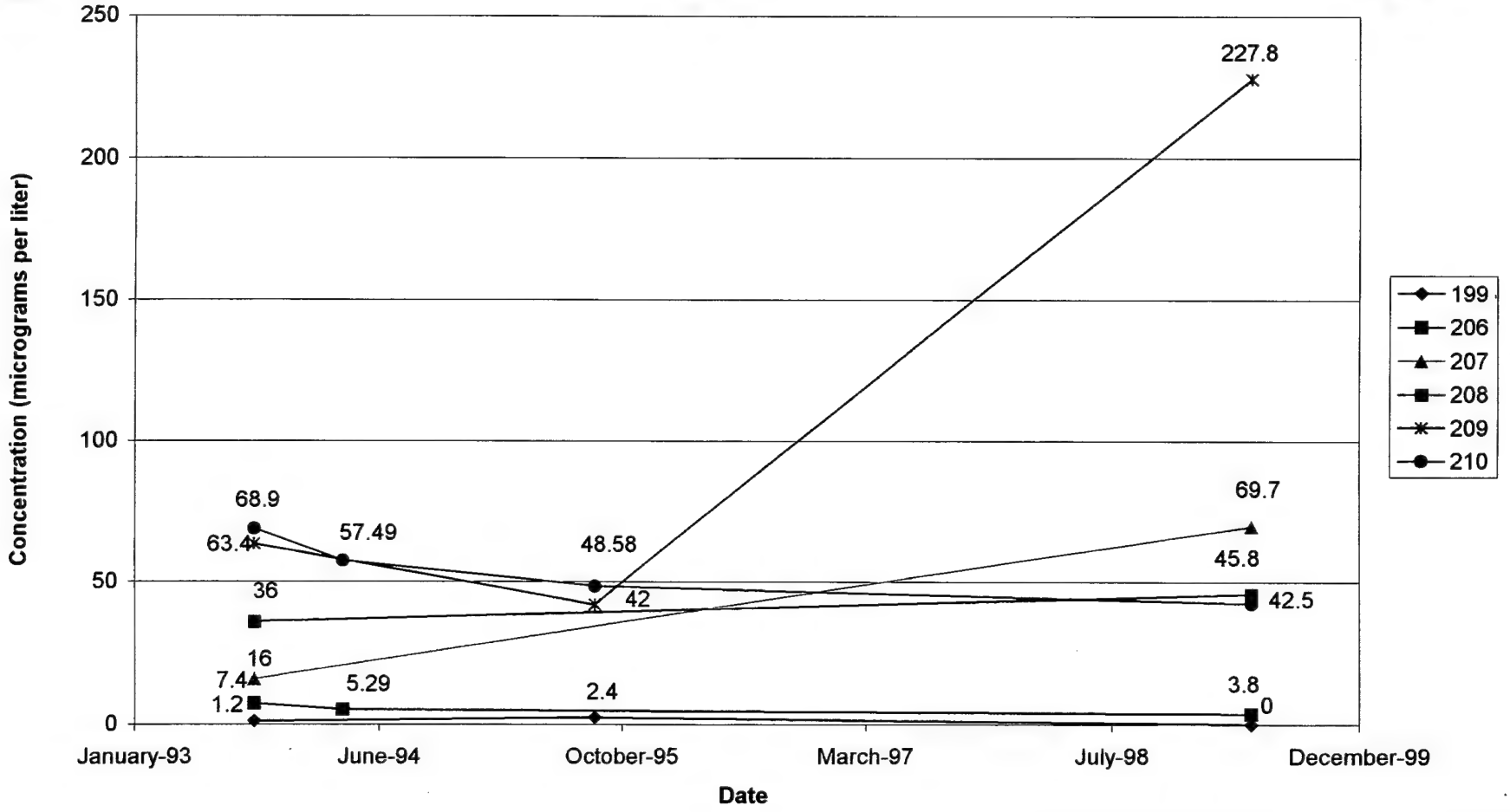

FIGURE 4.8

TOTAL CHLORINATED ETHENES VERSUS TIME

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measured core of the CAH contaminant plume has not attenuated over the period from 1993 to 1999.

Concentrations of TCE, *cis*-1,2-DCE, *trans*-1,2-DCE, and VC versus time for well 209 are shown on Figure 4.9. Well 209 has consistently exhibited the highest detected concentrations at the site, and it is assumed to represent dissolved contaminant concentrations at or immediately downgradient from the primary source area. Concentrations at well 209 show a discernible upward trend, indicating that the source of chlorinated ethenes at LF-03 has not attenuated. However, from July/November 1993 to May 1999, TCE concentrations have decreased from 44 to 26.7 µg/L, and from 19 to 7.5 µg/L, respectively, at two wells (210 and 211) located further downgradient along the plume migration pathway. An accurate assessment regarding the degree to which the chlorinated ethene plume is at equilibrium (neither expanding nor receding) cannot be made on the basis of the available data.

4.3.2 Presence of Daughter Products and CAH Ratios

The presence of daughter products that were not used in Base operations, particularly *cis*-1,2-DCE, provides strong evidence that TCE is being reductively dehalogenated. However, as described above, the low magnitude of daughter product concentrations relative to TCE indicated that the degree to which this transformation is occurring is limited.

Progressive transformation of TCE to *cis*-1,2-DCE as the contamination migrates away from the source area can be indicated by computing the molar ratio of parent compounds to daughter products at different distances from the source area. The ratios of TCE to *cis*-1,2-DCE in groundwater samples from four wells located along the axis of the TCE plume (209, 210, 211, 199) during three different sampling events (October 1993, September 1995, and May 1999) are shown on Figure 4.10. No data were collected for well 211 in September 1995, and TCE or DCE were not detected at well 199 during the May 1999 sampling event. Consequently, there are no data points for these two wells for the sampling events mentioned. Because reductive dehalogenation proceeds in only one direction (i.e., TCE to DCE and not vice versa), the TCE to DCE ratio would decrease along the flowpath where reductive dehalogenation of TCE dominates the contaminant attenuation process. The lowest ratio for all three sampling events is found at well 209, indicating that TCE is being reductively dehalogenated most significantly in and immediately downgradient from the suspected source area. However, downgradient from 209, the ratio begins to increase for each sampling event. This means that *cis*-1,2-DCE concentrations are decreasing more rapidly than TCE concentrations. Because VC (the DCE reductive dehalogenation metabolite) is not observed, DCE oxidation is inferred. Because optimal conditions for DCE oxidation implies less-than-optimal conditions for TCE reductive dehalogenation, TCE biodegradation is assumed to cease downgradient from well 209.

4.3.3 Chloride as an Indicator of Dehalogenation

Chloride ions are removed from chlorinated solvents and enter solution during biodegradation, whether via reductive dehalogenation or aerobic oxidation. Therefore,

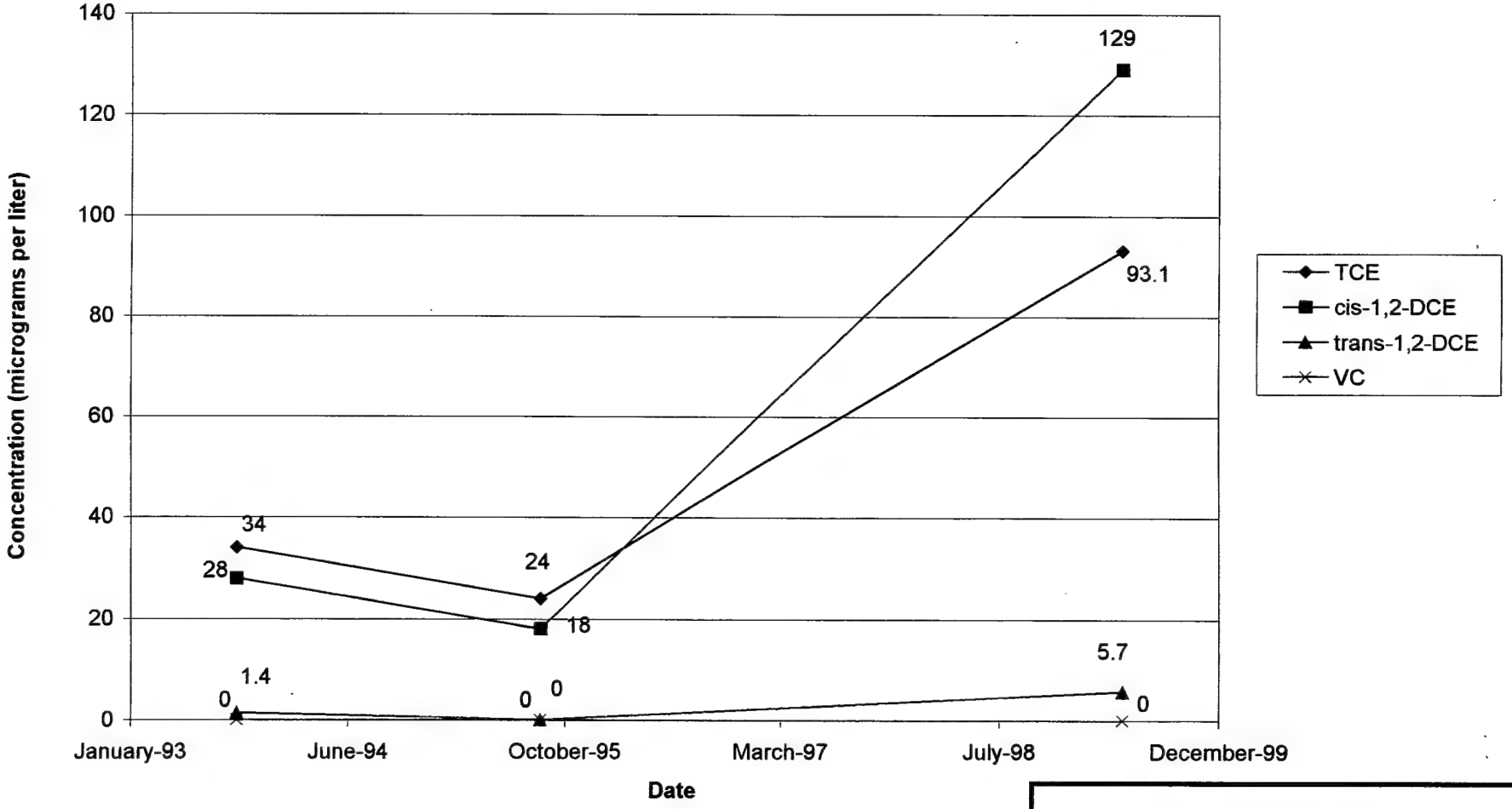

FIGURE 4.9

TCE, cis-1,2-DCE, TRANS-1,2-DCE, AND VC vs TIME AT WELL 209

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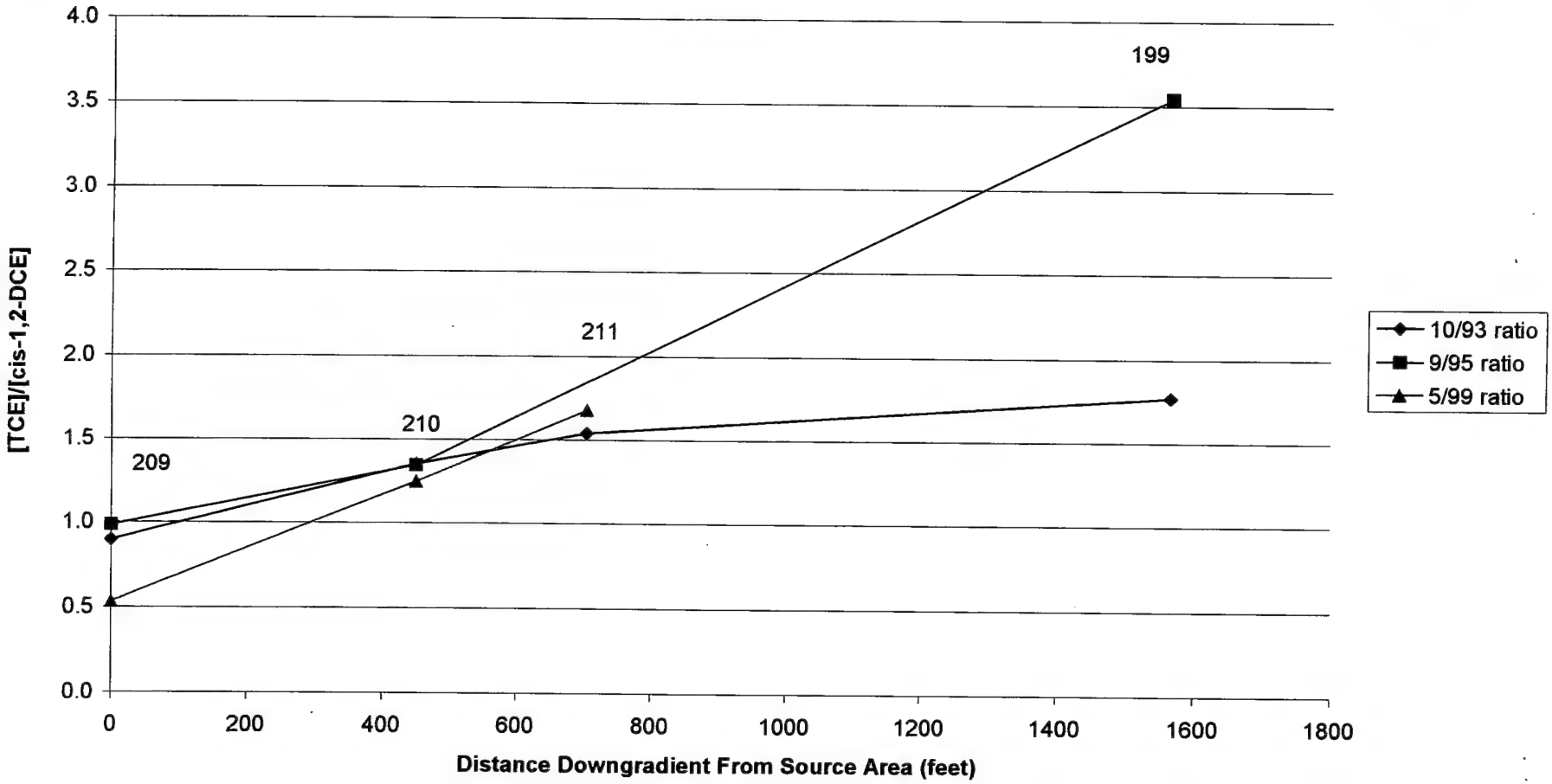

FIGURE 4.10

RATIO OF TCE TO cis-1,2-DCE vs DISTANCE FROM SOURCE AREA OCTOBER 1993 TO MAY 1999

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chloride concentrations in groundwater should increase above background levels in areas where reductive dehalogenation or aerobic biodegradation are taking place.

Chloride concentrations measured in May 1999 are presented in Table 4.5, and Figure 4.11 shows the distribution of chloride in groundwater at the site. Background chloride concentrations in groundwater range from about 2.54 milligrams per liter (mg/L) to 43.6 mg/L, and averaged 21.37 mg/L based on data from wells 64, 196, 197, 198, 233, and 232. Each of these wells is upgradient or crossgradient from areas containing significant dissolved CAH concentrations. The highest chloride concentrations were detected downgradient from the TCE plume. Analytical data indicate that chloride, generated as a byproduct of reductive dehalogenation occurring in the TCE plume and oxidation of the resulting DCE plume, is migrating in the direction of groundwater flow.

4.3.4 ORP as an Indicator of Redox Processes

Redox potential is a measure of the relative tendency of a solution to accept or transfer electrons. The redox potential of a groundwater system depends on which electron acceptors are being reduced by microbes during oxidation of organic compounds. For example, by coupling the oxidation of fuel hydrocarbon compounds (or native organic carbon), which requires energy, to the reduction of other compounds (e.g., oxygen, nitrate, manganese, ferric iron, sulfate, carbon dioxide, and possibly *cis*-1,2-DCE), which yields energy, the overall reaction will yield energy.

The sequence of microbially mediated redox processes and the approximate ranges of ORPs that are favorable for each process are presented in Figure 4.12. In general, reactions yielding more energy tend to take precedence over processes that yield less energy (Stumm and Morgan, 1981; Godsey, 1994; Reinhard et al., 1994). Oxygen reduction would be expected in an aerobic environment with microorganisms capable of aerobic respiration, because oxygen reduction yields significant energy (Bouwer, 1992; Chapelle, 1993). However, once the available DO is depleted and anaerobic conditions dominate the interior regions of a contaminant plume, anaerobic microorganisms can utilize other electron acceptors in the following order of preference: nitrate (denitrification), manganese (manganese reduction), ferric iron (iron reduction), sulfate (sulfate reduction), and finally carbon dioxide (methanogenesis). Each successive redox reaction provides less energy to the system, and each step down in redox energy yield is paralleled by an ecological succession of microorganisms capable of facilitating the pertinent redox reactions.

Redox potentials were measured at groundwater monitoring wells sampled in May 1999. Redox potentials for groundwater at the site range from 29.9 millivolts (mV) to 276 mV (Table 4.5), which is outside the optimal range for reductive dehalogenation (although within the possible range). Isopleths for redox potential are displayed on Figure 4.13. Redox potential of groundwater at the site is somewhat more reduced in the locations with elevated concentrations of TCE and cis-1,2-DCE.

The lowest redox potentials were detected in the vicinity of PES-1S (58.9 mV) and PES-6S (29.9). These wells are located along the apparent centerline of the dissolved

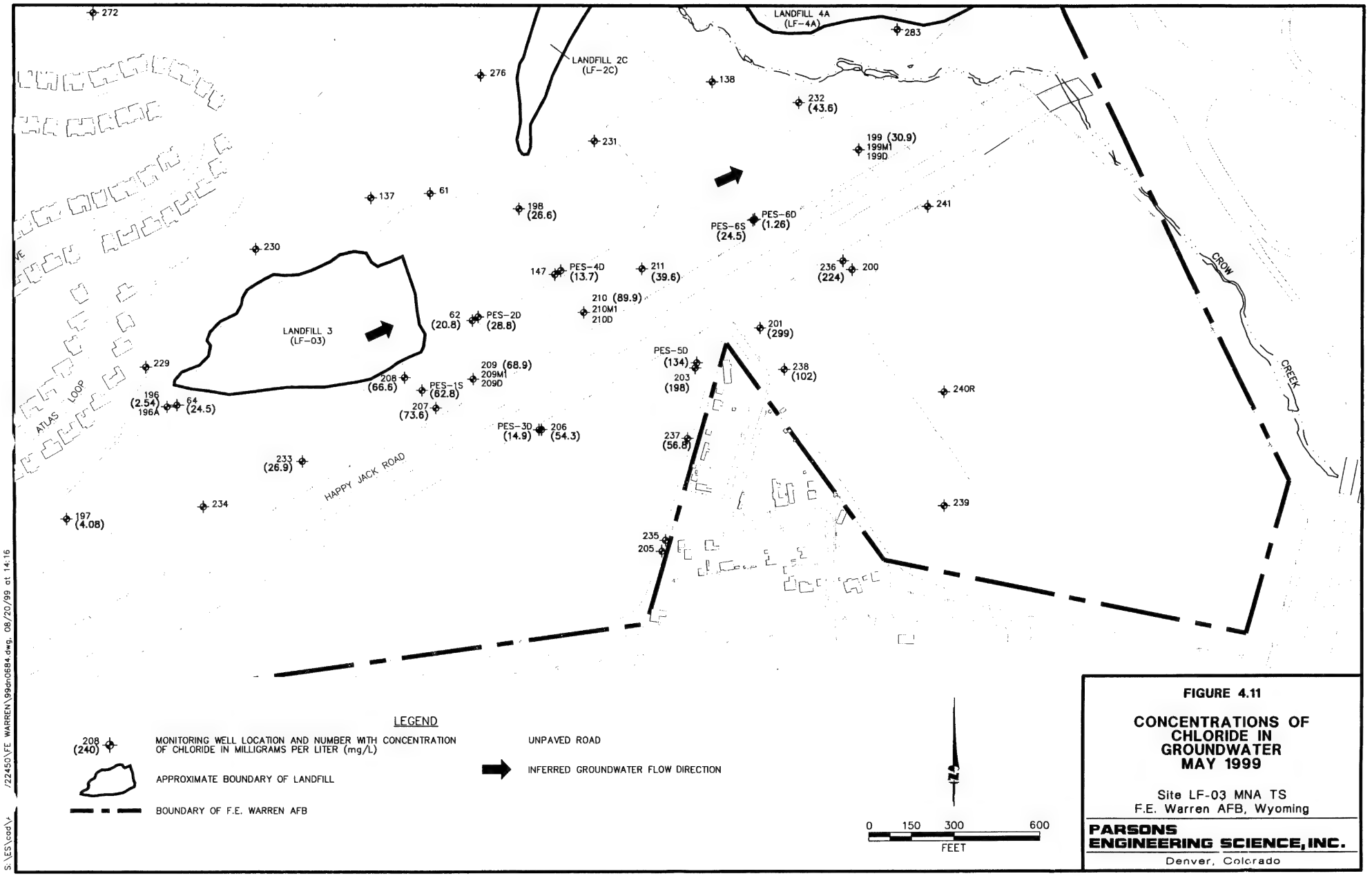

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FIGURE 4.11

CONCENTRATIONS OF CHLORIDE IN GROUNDWATER MAY 1999

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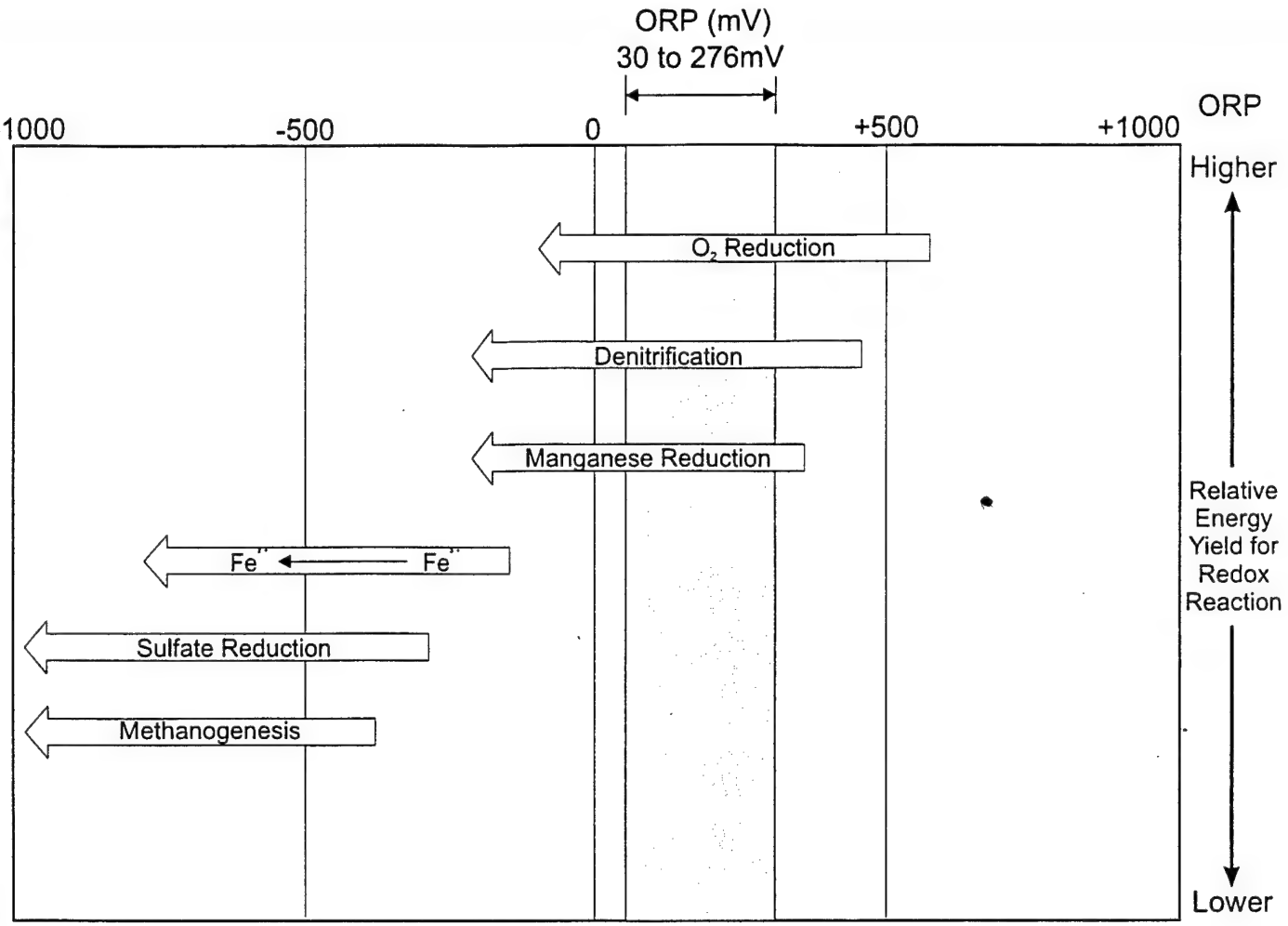

Notes

ORP = Oxidation Reduction Potential

Range of ORP measured at LF-03

1. These reactions would be expected to occur in sequence if the system is moving toward equilibrium.

2. These redox processes occur in order of their energy-yielding potential (provided microorganisms are available to mediate a specific reaction). Reduction of a highly oxidized species decreases the ORP of the system.

3. The ORP of the system determines which electron acceptors are available for organic carbon oxidation.

4. Redox reaction sequence is paralleled by an ecological succession of biological mediators.

Adapted from Stumm and Morgan, 1981.

FIGURE 4.12

SEQUENCE OF MICROBIALLY MEDIATED REDOX PROCESSES

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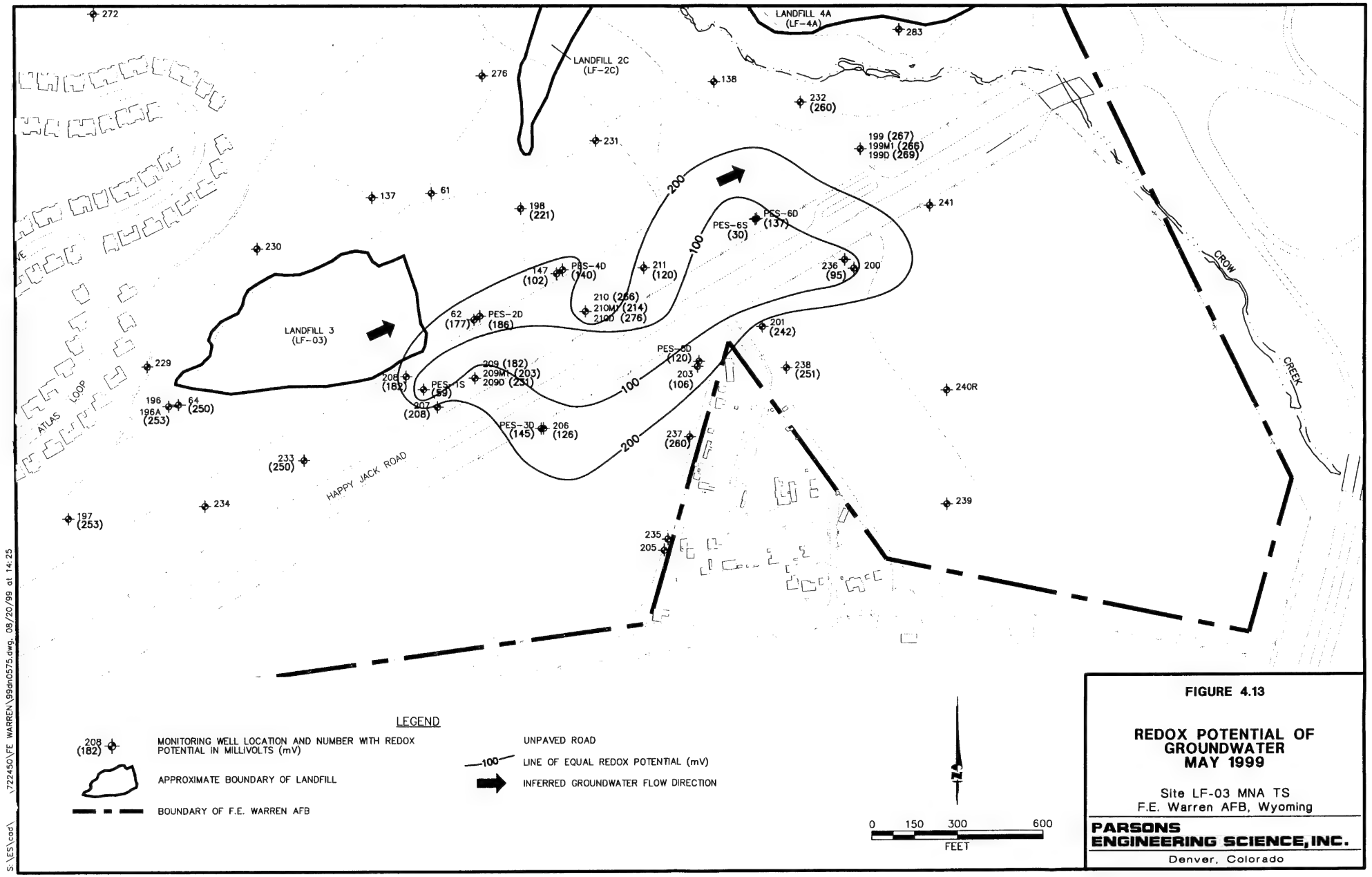

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FIGURE 4.13

REDOX POTENTIAL OF GROUNDWATER MAY 1999

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CAH plume core. This area of relatively low redox potential may reflect reducing conditions caused by the biodegradation of chlorinated solvents present at the site.

4.3.5 Electron Donors

The distribution of potential electron donors (carbon sources) such as BTEX, native organic carbon, or CAHs themselves are useful for evaluating the feasibility of reductive dehalogenation, aerobic biodegradation, or cometabolism (i.e., biodegradation reactions involving another substrate).

4.3.5.1 Organic Carbon in Groundwater

Dissolved organic carbon also can act as a source of electron donors during the reductive dehalogenation of CAHs. Dissolved TOC concentrations can be used as an indicator of the presence of such native carbon compounds in wells outside of the area containing dissolved contamination (anthropogenic organic compounds, such as CAHs, petroleum hydrocarbons, or landfill leachate also are measured by the TOC analytical method). Dissolved TOC concentrations in excess of 20 mg/L are desirable to drive dehalogenation reactions (Wiedemeier et al., 1996a).

TOC dissolved in groundwater was measured in groundwater samples collected in May 1999 (Table 4.5). Dissolved TOC concentrations detected in shallow groundwater at LF-03 range from 0.8 mg/L to 39.4 mg/L. The highest concentrations were measured in 196A, 197, PES-1S, PES-4D, and PES-5D and may reflect the presence of contamination. Elsewhere, the TOC concentrations did not exceed 24.6 mg/L. Native organic carbon concentrations of this magnitude are insufficient to drive reductive dehalogenation of CAHs.

4.3.5.2 Use of CAHs as Electron Donors

Less-chlorinated CAHs (e.g., DCE and VC) can be used as electron donors in aerobic environments, resulting in biodegradation of CAHs. Groundwater throughout most of the LF-03 contaminant plume is relatively aerobic (DO >1 mg/L), and the silty to sandy alluvial sediments do not have a particularly high native organic carbon content (Table 4.1). In these areas, TCE and DCE are probably being degraded through use as electron donors in microbially mediated redox reactions.

4.3.6 Alternate Electron Acceptors and Metabolic Byproducts

Biodegradation of organic compounds, whether natural or anthropogenic, brings about measurable changes in the chemistry of groundwater in the affected area. Concentrations of compounds used as electron acceptors (e.g., DO, nitrate, and sulfate) are depleted, and byproducts of electron acceptor reduction (e.g., iron (II), methane, and sulfide) are enhanced. By measuring these changes, it is possible to evaluate the importance of natural attenuation at a site.

Results of alternate electron acceptor and metabolic byproduct analyses for the TS are presented in Table 4.5. The following paragraphs discuss those parameters most useful in evaluating site biodegradation processes.

4.3.6.1 Dissolved Oxygen

DO concentrations were measured at monitoring wells during the May 1999 sampling event. Isopleths for DO concentrations are shown on Figure 4.14. DO concentrations ranged from 1.04 to 8.10 mg/L (Table 4.5), with the highest concentrations measured in wells upgradient and downgradient from the chlorinated solvent plume. Background DO concentrations are on the order of 7 to 8 mg/L.

DO concentrations within the chlorinated solvent plume indicate aerobic conditions. Reduced DO concentrations, relative to background concentrations, coinciding with the chlorinated solvent plume is a strong indication of biological activity.

4.3.6.2 Nitrate/Nitrite

After DO has been depleted in the microbiological treatment zone, nitrate may be used as an electron acceptor for anaerobic biodegradation of organic carbon via denitrification. Nitrate concentrations below background in areas with high organic carbon concentrations and low DO are indicative of denitrification. The oxidation of organic carbon via the process of denitrification (using nitrate as an electron acceptor) yields a relatively large amount of free energy to microbial populations.

Concentrations of nitrate/nitrite [as nitrogen (N)] were measured in groundwater samples collected in May 1999. Measured nitrate/nitrite (as N) concentrations are summarized in Table 4.5, and the distribution of nitrate/nitrite (as N) concentrations in site groundwater is shown on Figure 4.15. Background concentrations range from 1.65 mg/L to 16.6 mg/L. Within the plume, nitrate/nitrite concentrations generally range from 0.98 to 19.5 mg/L.

The distribution of nitrate/nitrite [as nitrogen (N)] in groundwater indicate that denitrification is not a significant process of biodegradation at the LF-03 site. Relatively low concentrations of nitrate/nitrite at several wells (207, 210D, PES6D) within the plume indicate that microbes may be utilizing nitrate as an electron acceptor for degradation of organic material (such as fuel hydrocarbons or native organic carbon) in portions of the plume. However, low concentrations of nitrate/nitrite within the plume core may be representative of background concentrations and not an indication of denitrification.

4.3.6.3 Ferrous Iron

The reduction of ferric iron [iron (III)] has been shown to be a major metabolic pathway for some microorganisms (Lovley and Phillips, 1988; Chapelle, 1993). The reduction of ferric iron results in the formation of ferrous iron [iron (II)], and elevated concentrations of iron (II) often are found in anaerobic groundwater systems. Ferrous iron concentrations once were attributed to the abiotic spontaneous and reversible reduction of ferric oxyhydroxides, which are thermodynamically unstable in the presence

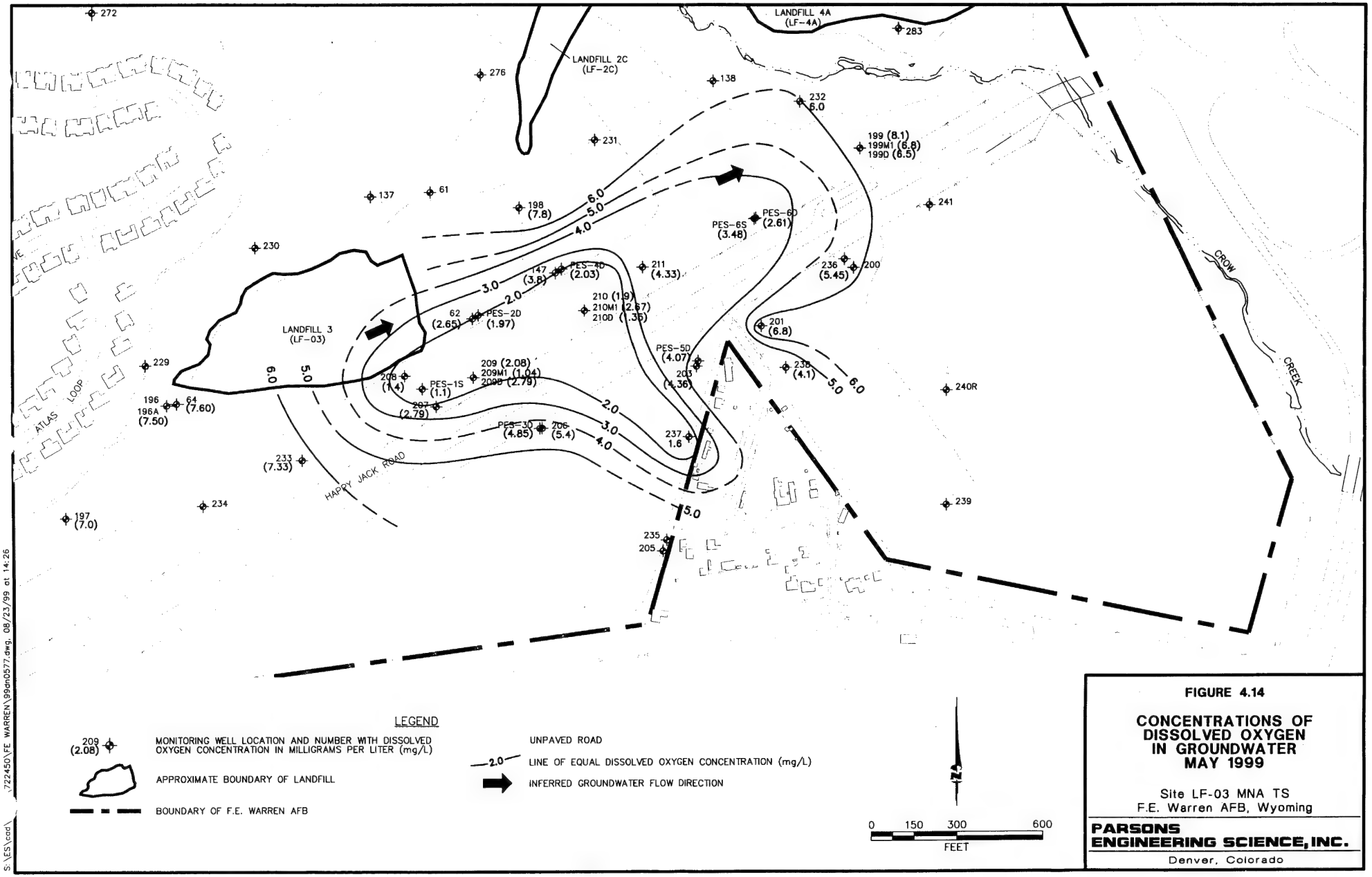

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FIGURE 4.14

CONCENTRATIONS OF DISSOLVED OXYGEN IN GROUNDWATER MAY 1999

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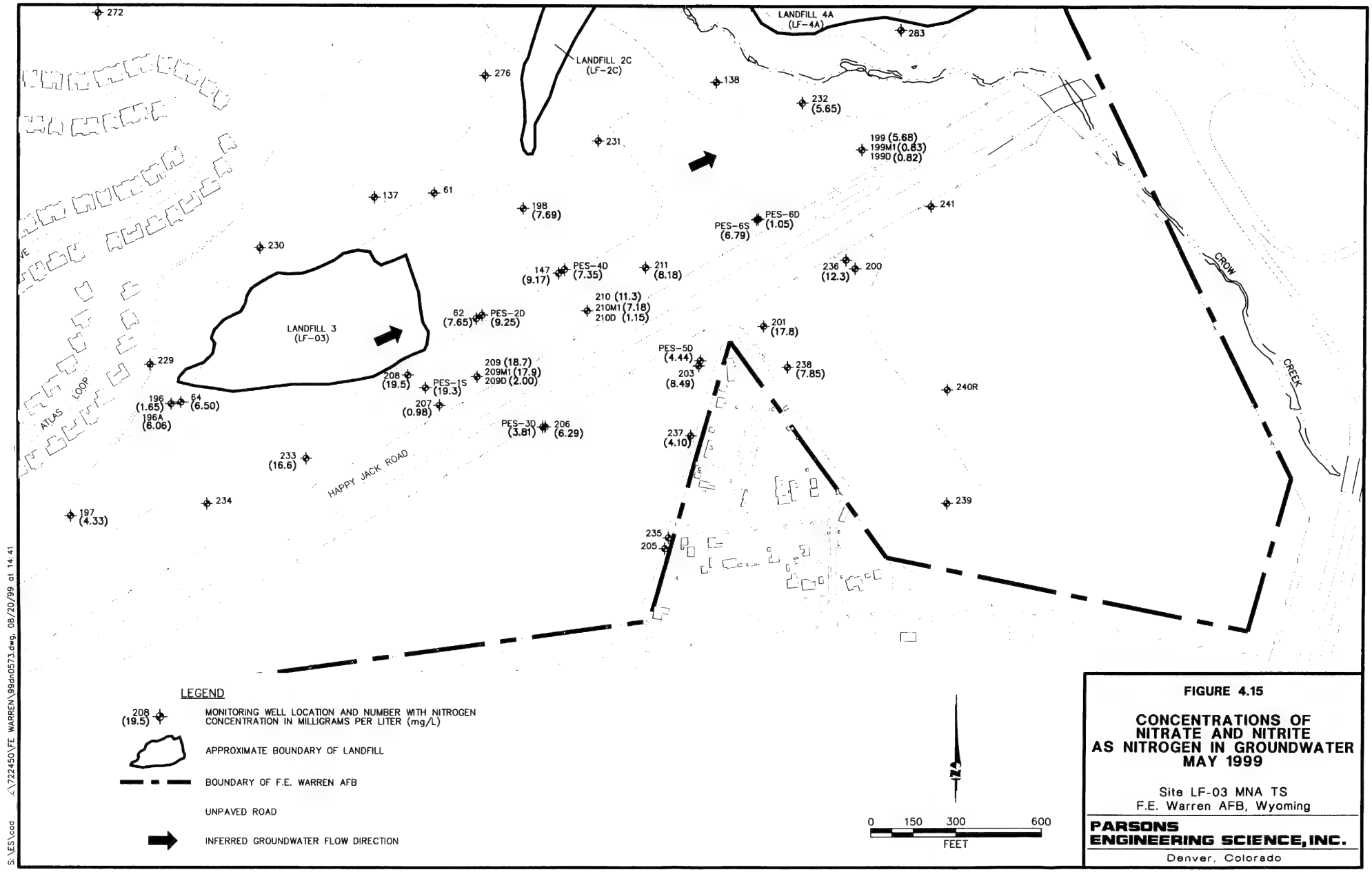

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FIGURE 4.15

CONCENTRATIONS OF NITRATE AND NITRITE AS NITROGEN IN GROUNDWATER MAY 1999

Site LF-03 MNA TS
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of organic compounds such as BTEX, TMB, and naphthalene. However, recent evidence suggests that the reduction of ferric iron cannot proceed at all without microbial mediation (Lovley and Phillips, 1988; Lovley *et al.,* 1991; Chapelle, 1993). None of the common organic compounds found in low-temperature, neutral, reducing groundwater could reduce ferric oxyhydroxides to iron (II) under sterile laboratory conditions (Lovley *et al.,* 1991). This means that the reduction of ferric iron requires mediation by microorganisms with the appropriate enzymatic capabilities.

Iron (II) concentrations measured in groundwater samples collected in May 1999 are summarized in Table 4.5. All iron (II) concentrations in LF-03 groundwater samples were less than the detection limit of 0.1 mg/L. This suggests that iron (III) hydroxide is not being reduced to iron (II) during biodegradation of native organic carbon, or chlorinated solvents.

4.3.6.4 Sulfate

Sulfate also may be used as an electron acceptor during microbial degradation of natural or anthropogenic organic carbon under anaerobic conditions (Grbic-Galic, 1990). This redox reaction is commonly called sulfate reduction.

Sulfate concentrations were measured in groundwater samples collected in May 1999. Sulfate concentrations in groundwater samples at the LF-03 site ranged from 9.51 mg/L to 487 mg/L (Table 4.5, Figure 4.16). Concentrations of sulfate in background wells ranged from 16.2 mg/L to 78.6 mg/L. Concentrations of sulfate within the chlorinated solvent plume ranged from 19.6 mg/L to 271 mg/L. The distribution of sulfate concentrations does not indicate reduced sulfate concentrations coinciding with chlorinated solvent concentrations. It is therefore unlikely that sulfate reduction is an ongoing anaerobic biodegradation process at LF-03.

4.3.6.5 Methane, Ethane, and Ethene in Groundwater

Although anaerobic degradation may occur under nitrate- and sulfate-reducing conditions (Vogel *et al.*, 1987; Chapelle, 1996), the most rapid biodegradation rates occur under methanogenic conditions (Bouwer, 1994).

Methane, ethane, and ethene concentrations were measured in groundwater samples collected in May 1999 (Table 4.5). Methane was detected at two locations at concentrations greater than 0.001 mg/L. Methane concentrations of 0.003 mg/L and 0.002 mg/L were detected at monitoring wells PES-3D and 237, respectively. Ethane and ethene were not detected in these wells above their respective quantitation limits of 0.002 mg/L and 0.003 mg/L.

Because of the aerobic conditions present in groundwater at the LF-03 site methanogenesis is not expected to be a significant process of biodegradation. The concentrations and distribution of methane in groundwater support this expectation.

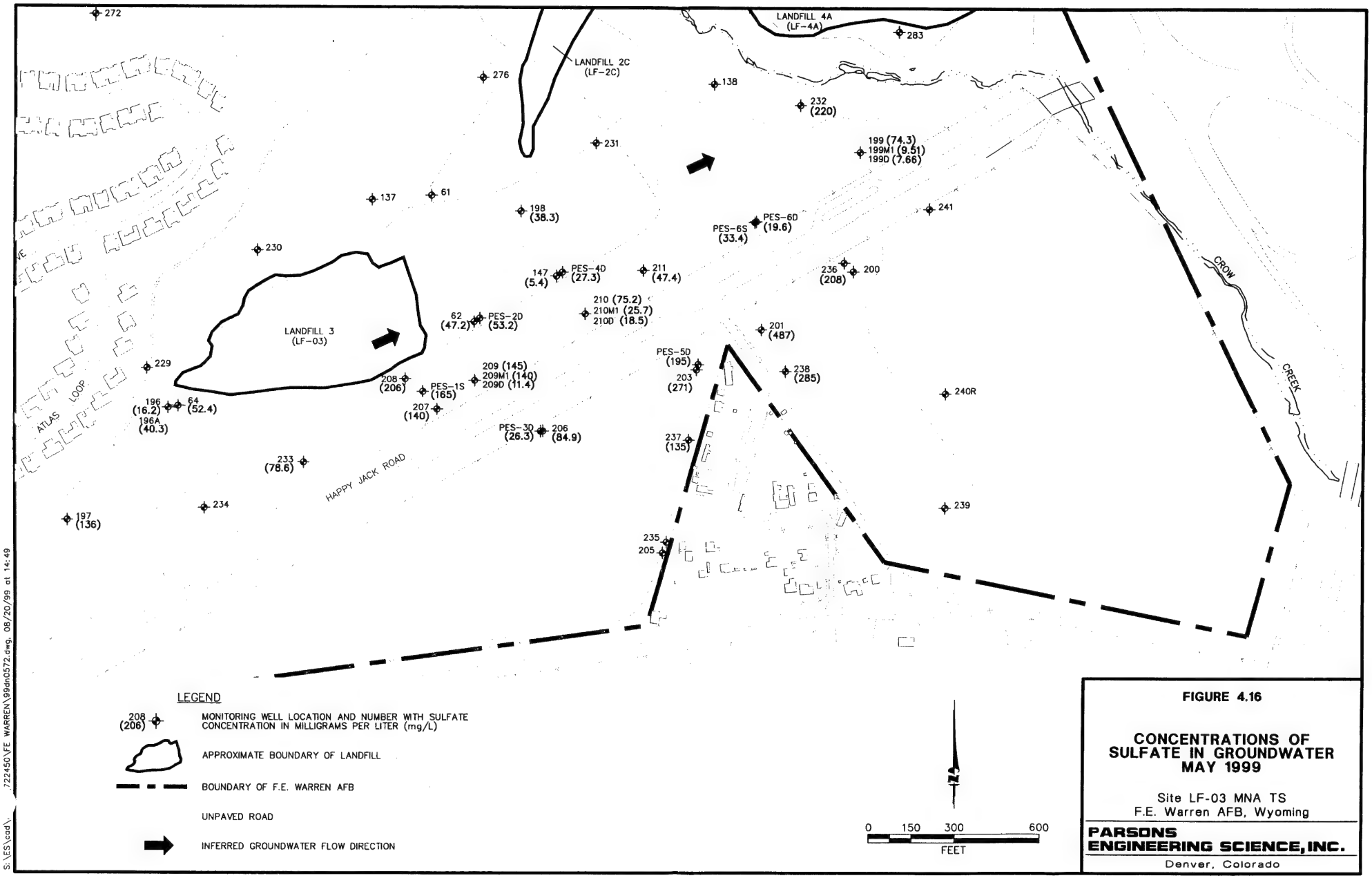

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FIGURE 4.16

CONCENTRATIONS OF SULFATE IN GROUNDWATER MAY 1999

Site LF-03 MNA TS
F.E. Warren AFB, Wyoming

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

4.3.6.6 Ammonia/Ammonium

The presence of ammonia in groundwater can result from either nitrate reduction (facilitated by microbes) or fixing of atmospheric nitrogen (also a microbial process). Because fixation of atmospheric nitrogen only occurs under reducing conditions [ORP less than -500 mV (Stumm and Morgan, 1981)], ammonia production via nitrate reduction is probably more common than by fixation of atmospheric nitrogen. In either case, the presence of ammonia in groundwater is a strong indication of microbial activity.

Ammonia was detected at one location (i.e., well 207 at 0.99 mg/L) at a concentration greater than 0.10 mg/L (Table 4.5). Because the distribution of nitrate concentrations in the aquifer at LF-03 did not indicate significant nitrate/nitrite reduction, elevated concentrations of ammonia are not expected.

4.3.7 Additional Geochemical Indicators

Other geochemical data collected for this evaluation can be used to further interpret and support the contaminant, electron donor, electron acceptor, and byproduct data previously discussed. These parameters provide additional qualitative indications of what processes may be operating at the site.

4.3.7.1 Alkalinity and Carbon Dioxide Evolution

Carbon dioxide is produced during the biodegradation of fuel hydrocarbons and native organic carbon compounds. In aquifers that have carbonate minerals as part of the matrix, carbon dioxide forms carbonic acid, which dissolves these minerals, increasing the alkalinity of the groundwater. An increase in alkalinity (measured as calcium carbonate [$CaCO_3$]) in an area with fuel hydrocarbons or chlorinated solvent (particularly less-chlorinated solvents) concentrations elevated above background conditions can be used to infer that fuel hydrocarbons, less-chlorinated solvents, or native organic carbon have been destroyed through aerobic and anaerobic microbial respiration.

Total alkalinity (as $CaCO_3$) was measured in groundwater samples collected in May 1999 (Table 4.5, Figure 4.17). Alkalinity is a measure of the ability of groundwater to buffer changes in pH. Total alkalinity in groundwater at the site varied from 120 mg/L to 300 mg/L. The range of alkalinity concentrations within the chlorinated solvent plume (120 mg/L to 240 mg/L) was ranged similar to the range of concentrations detected in background wells (140 mg/L to 220 mg/L). Alkalinity within the plume area is variable, but appears to be sufficient to buffer potential changes in pH caused by biologically mediated reactions. The pH data for site groundwater (Section 4.3.7.2) suggest that groundwater pH decreases slightly at some locations within the plume.

Free carbon dioxide concentrations also were measured in groundwater samples collected in May 1999 (Table 4.5, Figure 4.18). Carbon dioxide concentrations measured at the site range from 10 mg/L to 40 mg/L. Concentrations in background wells range from 15 mg/L to 25 mg/L. Within the plume area, concentrations range from 15 mg/L to 40 mg/L. Carbon dioxide concentrations above background could result from both aerobic and anaerobic biodegradation processes as contaminants are ultimately converted

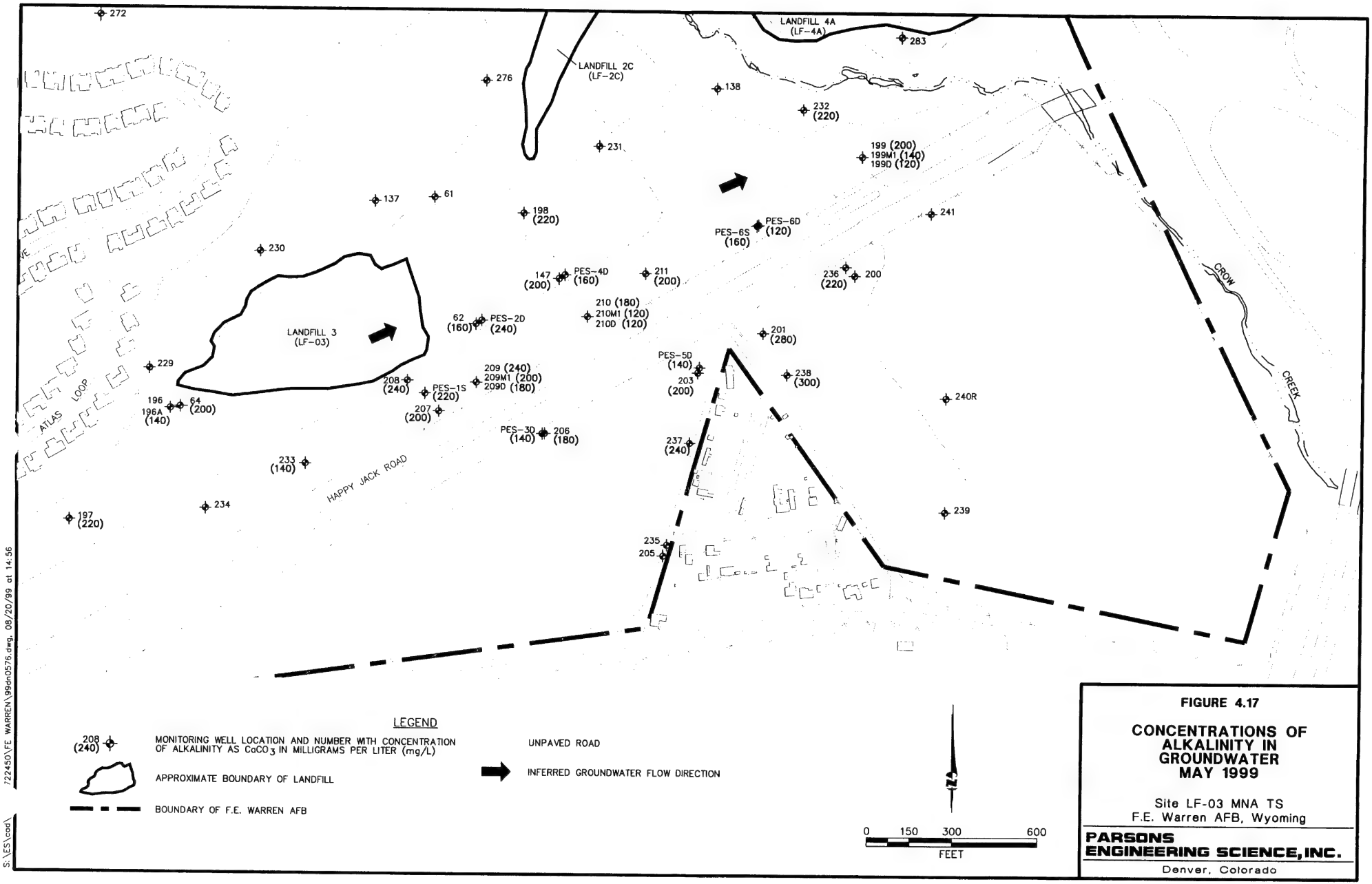

FIGURE 4.17

CONCENTRATIONS OF ALKALINITY IN GROUNDWATER MAY 1999

Site LF-03 MNA TS
F.E. Warren AFB, Wyoming

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

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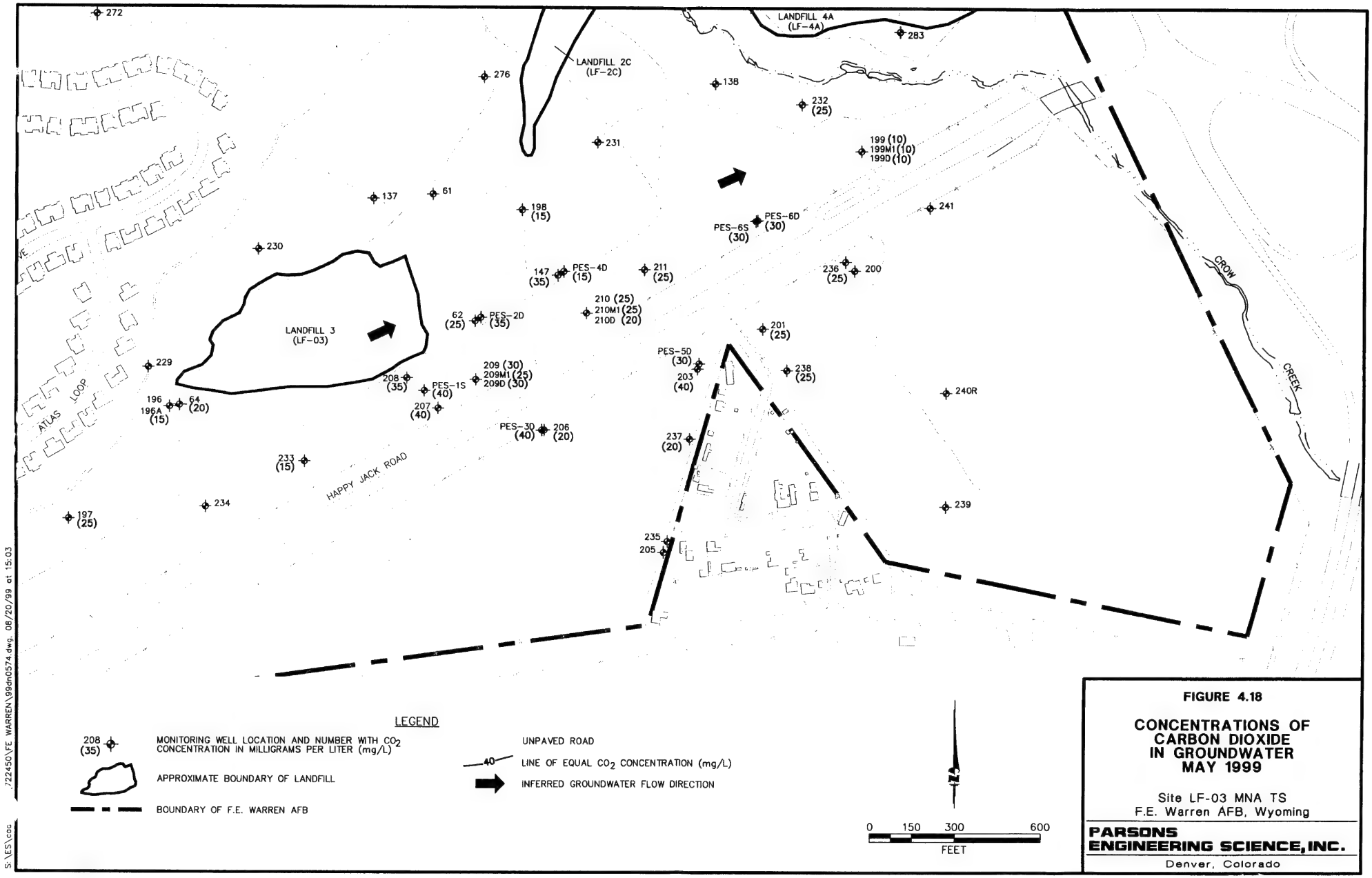

FIGURE 4.18

CONCENTRATIONS OF CARBON DIOXIDE IN GROUNDWATER MAY 1999

Site LF-03 MNA TS
F.E. Warren AFB, Wyoming

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

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to carbon dioxide and water. However, carbon dioxide concentrations within the extent of the chlorinated solvent plume are not elevated significantly above background concentrations.

4.3.7.2 pH

Groundwater pH was measured for samples collected from monitoring wells in May 1999 (Table 4.5). The pH of a solution is the negative logarithm of the hydrogen ion concentration [H^+]. Groundwater pH measured at the site ranges from 6.83 to 8.14 standard. With the exception of one pH measurement at the site, the range of pH is within the optimal range for CAH-degrading microbes of 6 to 8 standard units.

4.3.7.3 Temperature

Groundwater temperature was measured at monitoring wells in May 1999 (Table 4.5). Temperature can affect the types and growth rates of bacteria that can be supported in the groundwater environment, with higher temperatures typically resulting in higher growth rates. Wiedemeier *et al.* (1996a) report that biochemical processes are accelerated at groundwater temperatures greater than 20°C. Groundwater temperatures at LF-03 varied from 6.8 °C to 14.3 °C. These temperatures are below the optimal range for bacterial growth suggesting that bacterial growth rates may be somewhat retarded in groundwater at the site.

4.3.8 Screening Table for CAH Degradation

Wiedemeier *et al.* (1996a) present a worksheet to allow an initial assessment of the prominence of the natural attenuation of CAHs at a site. The worksheet, including the point values determined for LF-03, is included as Table 4.6. The interpretation of points awarded during the screening process outlined in Table 4.6 is shown in Table 4.7.

The score for LF-03 computed using Table 4.6 is 5. This score is consistent with the limited evidence for biodegradation of CAHs at LF-03.

4.4 APPROXIMATION OF BIODEGRADATION RATES

Biodegradation rate constants are necessary to accurately simulate the fate and transport of contaminants dissolved in groundwater. In many cases, biodegradation of contaminants can be approximated using first-order kinetics. First-order biodegradation rate constants may be calculated on the basis of field-scale data, or by using a small sample of the aquifer material and groundwater for microcosm studies. For reductive dehalogenation of chlorinated compounds, first-order rates are not necessarily an accurate representation because the degradation of CAHs depends on both concentration of electron donors (e.g., fuel hydrocarbons or native organic material) and the concentrations of electron acceptors (including inorganic acceptors and CAHs) (Moutoux *et al.*, 1996). Second-order rates would therefore allow more accurate modeling, but at this time there are no readily available groundwater contaminant transport models that can utilize such rates. Therefore, first-order rates must be estimated for use in a contaminant transport model.

TABLE 4.6
ANALYTICAL PARAMETERS AND WEIGHTING FOR PRELIMINARY SCREENING
Site LF-03 MNA TS
F.E. WARREN AFB, WYOMING

Analysis	Concentration in Most Contaminated Zone	Interpretation	Value	LF-03 Score
Oxygen	<0.5 mg/L	Tolerated, suppresses the reductive pathway at higher concentrations	3	0
	>1 mg/L	VC may be oxidized aerobically	-3	
Nitrate	<1 mg/L	At higher concentrations may compete with reductive pathway	2	1
Iron II	>1 mg/L	Reductive pathway possible	3	0
Sulfate	<20 mg/L	At higher concentrations may compete with reductive pathway	2	0
Sulfide	>1 mg/L	Reductive pathway possible	--	--
Methane	<0.5 mg/L	VC oxidizes	0	0
	>0.5 mg/L	Ultimate reductive daughter product, VC Accumulates	3	0
Oxidation Reduction Potential (ORP)	<50 millivolts (mV)	Reductive pathway possible	1	0
	<-100mV	Reductive pathway likely	2	0
pH	5 < pH < 9	Optimal range for reductive pathway	0	0
	5 > pH >9	Outside optimal range for reductive pathway	-2	0
TOC	> 20 mg/L	Carbon and energy source; drives dechlorination; can be natural or anthropogenic	2	1
Temperature	> 20°C	At T >20°C biochemical process is accelerated	1	0
Carbon Dioxide	>2x background	Ultimate oxidative daughter product	1	1
Alkalinity	>2x background	Results from interaction of carbon dioxide with aquifer minerals	1	0
Chloride	>2x background	Daughter product of organic chlorine	2	2
Hydrogen	>1 nM/L	Reductive pathway possible, VC may accumulate	3	--
	<1 nM/L	VC oxidized	0	
Volatile Fatty Acids	> 0.1 mg/L	Intermediates resulting from biodegradation of aromatic compounds; carbon and energy source	--	--
BTEX	> 0.1 mg/L	Carbon and energy source; drives dechlorination	2	0
PCE		Material released	0	0
TCE		Material released	0	0
		Daughter product of PCE	2 [a/]	
1,2-DCE		Material released	0	0
		Daughter product of TCE.	2 [a/]	2
		If *cis* is greater than 80% of total DCE it is likely a daughter product of TCE		
VC		Material released	0	0
		Daughter product of DCE	2 [a/]	0

TABLE 4.6 (Concluded)
ANALYTICAL PARAMETERS AND WEIGHTING FOR PRELIMINARY SCREENING
Site LF-03 MNA TS
F.E. WARREN AFB, WYOMING

Analysis	Concentration in Most Contaminated Zone	Interpretation	Value	LF-03 Score
Ethene/Ethane	>0.01mg/L >0.1 mg/L	Daughter product of VC/ethene	2 3	0 0
Chloroethane		Daughter product of VC under reducing conditions	--	--
1,1,1-Trichloroethane		Material released	0	--
1,2-Dichlorobenzene		Material released	0	--
1,3-Dichlorobenzene		Material released	0	--
1,4-Dichlorobenzene		Material released	0	--
Chlorobenzene		Material released or daughter product of dichlorobenzene	2[a]	--
1,1-DCE		Daughter product of TCE or chemical reaction of 1,1,1-TCA	2[a]	--
		TOTAL	**38**	**5**

[a] Points awarded only if it can be shown that the compound is a daughter product (i.e., not a constituent of the source NAPL).

TABLE 4.7
INTERPRETATION OF POINTS AWARDED DURING NATURAL ATTENUATION SCREENING
Site LF-03 MNA TS
F.E. WARREN AFB, WYOMING

Score	Interpretation
0 to 4	Inadequate evidence for biodegradation of chlorinated organics
5 to 12	Limited evidence for biodegradation of chlorinated organics
13 to 17	Adequate evidence for biodegradation of chlorinated organics
>17	Strong evidence for biodegradation of chlorinated organics

Microcosm studies can be used to show that the microorganisms necessary for biodegradation are present and to help quantify rates of biodegradation. Because microcosm studies are time consuming and expensive, they should be undertaken only at sites where there is considerable uncertainty concerning the biodegradation of

contaminants. Biodegradation rate constants determined by microcosm studies often are much higher than those observed in the field, and it may be inappropriate to use them to generate rate constants. The preferable method of contaminant biodegradation rate-constant determination is by use of field data, so no microcosm studies were conducted at the LF-03 site.

In order to calculate first-order biodegradation rate constants on the field scale, the apparent degradation rate must be normalized for the effects of dilution, dispersion, and sorption. Two methods for determining first-order rate constants for BTEX compounds are described by Wiedemeier *et al.* (1996a). One method involves the use of a biologically recalcitrant compound found in the dissolved contaminant plume that can be used as a conservative tracer. One organic compound that can be used at some sites is TMB. However, TMB was not detected at LF-03. For many chlorinated solvent plumes, chloride that is released to the groundwater during dehalogenation reactions also can serve as a tracer. Chloride was not used as a tracer for LF-03 due to the similarity between background chloride concentrations and those in the CAH plume. The other method, proposed by Buscheck and Alcantar (1995), involves interpretation of a steady-state contaminant plume and is based on the one-dimensional, steady-state analytical solution to the advection-dispersion equation presented by Bear (1979). Decay rates computed using this method account for chemical (abiotic) decay and biological (aerobic and anaerobic) decay. For an expanding plume, this first-order approximation can be viewed as an upper bound on the biodegradation rate. Use of this method overestimates biodegradation rate, because a typical expanding plume exhibits decreasing source area concentrations, increasing downgradient concentrations, or both. Over time, these changes result in a decreasing slope on a log-linear plot, and consequently a decreasing biodegradation rate. Both methods can be adapted to estimate rate constants for CAHs.

Another method for estimating reductive dehalogenation rates of CAHs is described by Moutoux *et al.* (1996). This method provides a total reductive dehalogenation rate for all dehalogenation steps. All rates (including the rapid TCE to DCE rate and the slow VC to ethene) are averaged together using the Moutoux *et al.* (1996) method. Because abiotic reactions and aerobic reactions that involve CAH compounds in the role of an electron donor are not included in this rate (and may in fact decrease the rate estimated by this method), the rate should be considered a lower bound on the destructive attenuation rate.

It should be noted that the magnitudes of the decay rates calculated using these methods are sensitive to the estimated migration velocity of the contaminant along the selected flowpath; therefore, inaccuracies in the estimated velocity will cause the decay rates to be less accurate. Overestimation of the groundwater velocity will result in overestimation of the decay rate, and vice versa.

The method of Buscheck and Alcantar (1995) was used to estimate first-order biodegradation rate constants for TCE, *cis*-1,2-DCE, and total chlorinated ethenes at LF-03. The method of Moutoux *et al.* (1996) also was used to estimate a first-order biodegradation rate constant for total chlorinated ethenes at LF-03. The decay rate calculations are summarized in Table 4.8 and Appendix E. Rate constants were not

TABLE 4.8
SUMMARY OF CHLORINATED SOLVENT DECAY RATES
MAY 1999
SITE LF-03 MNA TS
F.E. WARREN AFB, WYOMING

Contaminant	Sample Date	Flow Path	Analysis Method	Decay Rate (day^{-1})	Half Life (years)
TCE	May-99	209, 210, 211, PES-6S, 199	Buscheck and Alcantar[a/]	5.14E-05	37
cis-1,2-DCE	May-99	209, 210, 211, PES-6S, 199	Buscheck and Alcantar	1.03E-04	18
Total Chlorinated Ethenes	May-99	209, 210, 211, PES-6S, 199	Buscheck and Alcantar	6.96E-05	27
Total Chlorinated Ethenes	May-99	209, 210, 211, PES-6S, 199	Reductive Dechlorination[b/]	1.77E-06	1,073

[a/] Method of Buscheck and Alcantar (1995) for steady-state plumes.

[b/] Reductive Dechlorination by method of Moutoux et al. (1996), which gives decay rate attributable to reductive dechlorination.

calculated for BTEX compounds because of the very low remaining concentrations (Table 4.2).

The first-order, steady-state TCE decay rate computed using data from the flowpath including wells 209, 210, 211, PES-6S, and 199 and the method of Buscheck and Alcantar (1995) is 5.14E-05 day^{-1}, which corresponds to a half-life of 36.98 years. This flowpath extends from the inferred primary source area at well 209 to the leading edge of the dissolved TCE plume. These wells are all screened within the upper portion of the aquifer and therefore may not be representative of decay rates in groundwater in the lower portions of the aquifer. For *cis*-1,2-DCE, the calculated first order biodegradation rate is 1.03E-4 day^{-1}, which corresponds to a half life of 18.45 years.

Total chlorinated ethene degradation was calculated by both the methods of Buscheck and Alcantar (1995) and Moutoux, *et al.*, (1996). The first-order, steady-state, total chlorinated ethene decay rate computed using data from the flowpath 209, 210, 211, PES-6S, and 199 and the method of Buscheck and Alcantar (1995) is 6.964E-05 day^{-1}, which corresponds to a half-life of 27.27 years. This rate is very similar to that calculated for TCE alone. As described above, the decay rates computed using this method can be viewed as an upper bound on the biodegradation rate if the plume is expanding. Data presented in Section 4.2 suggests the possibility of a slowly expanding plume. Therefore, the computed decay rate should be considered an upper bound of the combined effects of both reductive dehalogenation occurring in the general source area and aerobic decay occurring downgradient.

An attempt was made to compute a lower bound dehalogenation rate along this same flowpath using the method of Moutoux *et al.* (1996). The corrected CAH concentration increased with distance along the flowpath between wells 209, 210, 211, PES-6S, and 199. The first-order, total reductive dehalogenation decay rate computed for total chlorinated ethenes using data from the flowpath 209, 210, 211, and PES-6S and the method of Moutoux (1996) is 1.770E-06 day^{-1}, which corresponds to a half-life of 1073 years. The total reductive dehalogenation biodegradation rate calculated by the Moutoux method indicates that reductive dehalogenation along this flow path is not applicable. This is probably due to the occurrence of aerobic biodegradation of TCE and/or DCE, because the method assumes that both parent and daughter CAHs are conserved along the selected flowpath. The failure of this method indicates that other biodegradation processes besides reductive dehalogenation (e.g., aerobic processes) are occurring along this flowpath.

4.5 SUMMARY

The dissolved CAH plume appears to have migrated 1520 feet northeast of the source area at LF-03. Several lines of chemical and geochemical evidence indicate that, although dissolved TCE at LF-03 is undergoing biologically facilitated reductive dehalogenation, the occurrence of this process is limited and localized. Near the source area, this is most clearly observed by a decreasing ratio of TCE to the primary metabolite *cis*-1,2-DCE. Downgradient from the source area, increasing TCE to DCE ratios suggest that DCE is degraded through oxidation reactions, while TCE mass is relatively unaffected by destructive attenuation mechanisms. As a result, the parent CAH (TCE)

still comprises the majority of the contamination present in groundwater throughout most of the plume. The dissolved CAH plume at LF-03 exhibits characteristics of predominantly Type 3 behavior, with some indications of Type 1 behavior evidenced in and immediately downgradient from the source area. The evidence supporting the limited occurrence of TCE biodegradation is summarized below.

- The presence of *cis*-1,2-DCE is a direct indication that TCE is being reductively dehalogenated, but the increasing TCE to DCE ratios indicate that reductive transformation of TCE is very limited;
- The presence of elevated chloride concentrations (above background levels) is very localized, indicating that reductive dehalogenation reactions are not prevalent enough in many portions of the plume to significantly influence chloride concentrations;
- ORP data indicate that the groundwater is reducing enough to sufficiently to support the occurrence of reductive dehalogenation, but redox conditions are not optimal for this process;
- Dissolved TOC concentrations are not sufficient to sustainably drive dehalogenation reactions;
- The lack of true anaerobic conditions throughout the majority of the TCE plume probably limits the occurrence of reductive dehalogenation, which is an anaerobic process;
- Nitrate and sulfate concentrations within the plume area are sufficiently high that use of CAHs as electron acceptors may be inhibited due to the preferential use of these anions as alternate electron acceptors; and
- The evidence that methanogenic conditions existed near the source area indicates that conditions favorable for reductive dehalogenation of CAHs were at least locally present; however, methane was infrequently detected and, where present, occurred at very low concentrations, indicating that the occurrence of methanogenesis was spatially and temporally very limited.

As discussed in Section 4.5, rates of CAH biodegradation estimated from data collected for this investigation range from 6.964E-05 day^{-1} to 1.770E-06 day^{-1}. An average decay rate that is intermediate between these bounding values (e.g. 3.6E-05 day^{-1}) may be most representative of the overall LF-03 CAH plume.

SECTION 5

GROUNDWATER FLOW AND CONTAMINANT TRANSPORT MODEL

Computer simulations of groundwater flow and contaminant are used to evaluate the future migration and natural attenuation of TCE dissolved in groundwater at F.E. Warren AFB LF-03. The model was developed using site-specific data and conservative assumptions about governing physical and chemical processes.

5.1 GENERAL OVERVIEW AND MODEL DESCRIPTION

The computer programs "A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model" (MODFLOW) (McDonald and Harbaugh, 1988) and MT3D96 (Zheng, 1990; Papadopulos, 1996) were used to evaluate dissolved TCE at the site. MODFLOW was used to compute hydraulic heads and groundwater flux. MT3D96 was used to compute solute transport of dissolved TCE due to advection, dispersion, adsorption, and biodegradation. The pre- and post-processors contained in Visual MODFLOW, Version 2.8.0 (Waterloo Hydrogeologic Software, 1999) were used to build a site-specific model for Site LF-03 at F.E. Warren AFB. The graphic user interface facilitated model development and analysis as well as presentation of model results.

MODFLOW is a three-dimensional groundwater flow simulation computer program published by the USGS (McDonald and Harbaugh, 1988) and incorporated into Visual MODFLOW. MODFLOW uses implicit solution techniques to solve the transient groundwater flow equation for hydraulic head (McDonald and Harbaugh, 1988). The solution techniques are based on a one-, two-, or three-dimensional, block-centered, finite difference grid, which is superimposed on the model area. The aquifer properties can be heterogeneous and anisotropic, and aquifer layers can be simulated as confined, unconfined, or a combination of both (McDonald and Harbaugh, 1988). Results of a MODFLOW simulation include the distribution of hydraulic head within each model layer as well as groundwater flux through the model area.

The MT3D96 code incorporates advection, dispersion, sorption, and biodegradation to simulate contaminant plume migration and degradation. The MODFLOW-computed hydraulic heads and groundwater flux are used by MT3D96 to compute groundwater flow velocity and thus solute transport. MT3D96 offers solution routines based on the Method of Characteristics (MOC) and an upstream finite difference technique. The MOC solute transport model was developed by Konikow and Bredehoeft (1978) for the USGS two-dimensional (2-D) MOC model code. The MOC model was modified by Zheng (1990) to allow three-dimensional (3-D) solutions, and to allow use of a modified MOC that reduces numerical dispersion. The modified model is called MT3D. S.S. Papadopulos

and Associates (1996) modified version 1.5 of MT3D by adding detailed mass budgets and cell-by-cell specification of chemical reaction coefficients. The resulting code is MT3D96. Both MT3D and MT3D96 are incorporated into Visual MODFLOW 2.8.0. Due to mass balance discrepancies often associated with use of MOC solvers, MT3D96's upstream finite difference solver was used for this modeling exercise.

5.2 MODEL OBJECTIVES

The modeling effort had three primary objectives: 1) predict the future extent and concentrations of the dissolved TCE contaminant plume by modeling the combined effects of advection, dispersion, sorption, and biodegradation; 2) assess the potential for downgradient receptors to be exposed to contaminants (TCE) at concentrations above regulatory levels of concern; and 3) if applicable, provide technical support for the natural attenuation remedial option at post-modeling regulatory negotiations. Specifically, the MT3D96 simulations for LF-03 were constructed to address the following questions:

- Does the observed distribution of TCE accurately reflect measured groundwater flow conditions or assumed source configuration?
- What groundwater flow conditions (hydraulic conductivity, hydraulic anisotropy) would account for the observed distribution of TCE?
- What source configuration can account for the observed TCE distribution?
- To what extent is natural attenuation controlling the TCE plume at this site?
- How will various remedial alternatives affect TCE plume migration and groundwater concentrations?

5.3 CONCEPTUAL MODEL DESIGN AND ASSUMPTIONS

The area of concern for this model includes the area incorporating LF-03 and the downgradient contaminant flow path, especially where TCE has been detected in association with the inferred LF-03 source area. The hydrogeology of the model area is described in detail in Section 3. As described in that section, shallow groundwater flows east-northeast from LF-03 toward Crow Creek (approximately 2,000 feet away), where significant discharge is assumed to occur. No hydrograph or river stage data are available to estimate the discharge to Crow Creek.

It appears that, if the TCE plume reaches Crow Creek, it will do so approximately 600 to 900 feet upstream of where the creek crosses the base boundary. It is assumed that a portion of the TCE would discharge to the creek and flow to the base boundary; another portion would remain in groundwater and flow along the creek basin to the base boundary; and any remaining TCE might possibly cross the creek at greater depths and continue migrating toward the east-northeast. However, Crow Creek and its immediate surroundings are not characterized well enough to estimate potential water and TCE flux along these pathways. For the present exercise, it was conservatively assumed that any TCE will discharge to Crow Creek or remain in Crow Creek basin groundwater, and thus

be transported along the creek to the site boundary. This was accomplished by specification of appropriate hydraulic head boundary conditions.

Groundwater flow in the LF-03 area is through Quaternary surficial deposits (which are thickest along streams) and the Upper Ogallala Formation. Both types of deposits are heterogeneous mixtures of clay, silt, sand, and gravel characteristic of braided stream environments. Boring logs indicate that coarser sediments are more prevalent within 20 to 30 feet of the shallow water table, and sediments are generally finer below this. No TCE has been detected at depths greater than about 40 feet below the water table (Figure 4.5). TCE vertical concentration gradients are relatively low within 40 feet of the water table, indicating a relatively high degree of connectivity among the shallow saturated strata.

A 3-D model was utilized to simulate the vertical distribution of TCE. Because the primary contaminant transport appears to be limited to the top 40 feet of the shallow saturated zone, it was assumed that the system could be adequately represented by a 3-layer model. The upper layer corresponds to the depth interval containing monitoring wells screened near the water table. The lower layer corresponds to the depth interval containing monitoring wells with mid-level screened intervals. An intermediate layer separates these two depth intervals. As mentioned above, TCE has not been detected in groundwater samples collected from deeper monitoring wells screened more than forty feet below the shallow water table. Therefore, the bottom of the third layer was specified as a no-flow surface. The top layer extended from the ground surface to approximately 10 feet below the water table, and the second and third layers were each 15 feet thick, resulting in a model simulating the top 40 feet of the shallow saturated zone.

All three layers were assumed to be hydraulically connected, with the presence of vertical hydraulic gradients largely ignored. An exception to this was in the Crow Creek region, where upward gradients were induced through specification of boundary heads. Due to the lack of data regarding base flow and depths of Crow Creek, it was defined as a linear specified-head feature, with heads estimated from ground surface elevation maps. In the top model layer, elevated hydraulic conductivity was specified along a narrow zone bordering the creek. Other than this feature, all conductivities were considered uniform with depth due to the somewhat random, small-scale lithologic variations and evidence of vertical transport within the 40-foot model thickness.

It is likely that contaminants were first introduced into the groundwater at this site as a result of leaking landfill wastes, spills, or dumping. It was assumed that contaminants entered the groundwater shortly after LF-03 opened in 1960, and that residual NAPL contamination associated with the leached waste has acted as a continuous source. It was also assumed that no new sources have been placed in or near the landfill since the early 1990's, and all subsequent contaminant loading (including future loading) is due to residual sources. For predictive simulations, it was assumed that the residual sources will continue to weather (lose mass) due to processes such as volatilization, dissolution, and biodegradation, and that the mass of contaminants entering groundwater will continuously decline

Important assumptions made when using the MT3D96 code are that dispersion, sorption, and biodegradation are significant factors controlling contaminant fate and

transport. Dispersivity, which is a characteristic of the porous medium, is a measure of the longitudinal, lateral, and vertical spreading of the contaminant plume. Such spreading is due to local heterogeneities that cause deviations from the average linear solute migration velocity. The magnitude of dispersion is generally believed to be scale-dependent: the longer the plume flowpath, the greater the dispersion. Given the considerable length of the TCE plume (approximately 1,800 feet) and the documented presence of subsurface heterogeneities (Section 3), it is reasonable to assume that dispersion is an important parameter influencing solute transport in the study area. According to data presented in Sections 3 and 4, soil organic carbon concentrations are relatively low. Even with low organic carbon, sorption may still be a significant, if not dominant, mechanism affecting transport. Data also suggest that both anaerobic and aerobic biodegradation of TCE are occurring within the contaminant plume. Dispersion was estimated using literature values and accepted rules-of-thumb, sorption (assumed to be a linear process) was simulated using a coefficient of retardation, and biodegradation was simulated using a first-order decay constant. Selection of values for these model-input parameters is discussed in Section 5.4.3.

5.4 INITIAL MODEL SETUP

The initial setup for this model was based on site-specific data where possible. Where site-specific data were not available (e.g., for effective porosity), reasonable assumptions were made on the basis of widely accepted literature values for materials similar to those found in the shallow saturated zone at LF-03. The following sections describe the basic model setup. Parameters varied during model calibration are discussed in Section 5.5.

5.4.1 Grid Design

The model area for LF-03 includes the landfill source area and the downgradient area encompassing the TCE plume, Crow Creek, and the base boundary. The model domain for LF-03 is represented using three layers, with a 220-cell by 125-cell horizontal grid (Figure 5.1). The long axis of the model grid is oriented toward the east-northeast, parallel to the direction of shallow groundwater flow and the axis of the observed TCE plume. The model cells were uniform in size, with dimensions of 20 feet by 20 feet. Significant portions of the grid in the northwest and southwest corners were specified as inactive for flow solutions. Inactive flow boundaries were drawn normal to estimated piezometric head contours so that resulting no-flow conditions normal to the boundaries were an accurate reflection of field conditions. Use of inactive flow zones (Figure 5.1) increased computational efficiency, and kept flow boundaries closer to observation wells allowing for a more accurate simulation of boundary conditions. Similarly, inactive transport zones were used to limit transport calculations to zones surrounding and downstream of observed TCE contamination (Figure 5.1).

5.4.2 Model Layers

Due to the somewhat random spatial distribution of lithologies in the model region, grid layers were specified without regard to individual hydrogeological units. Instead, the

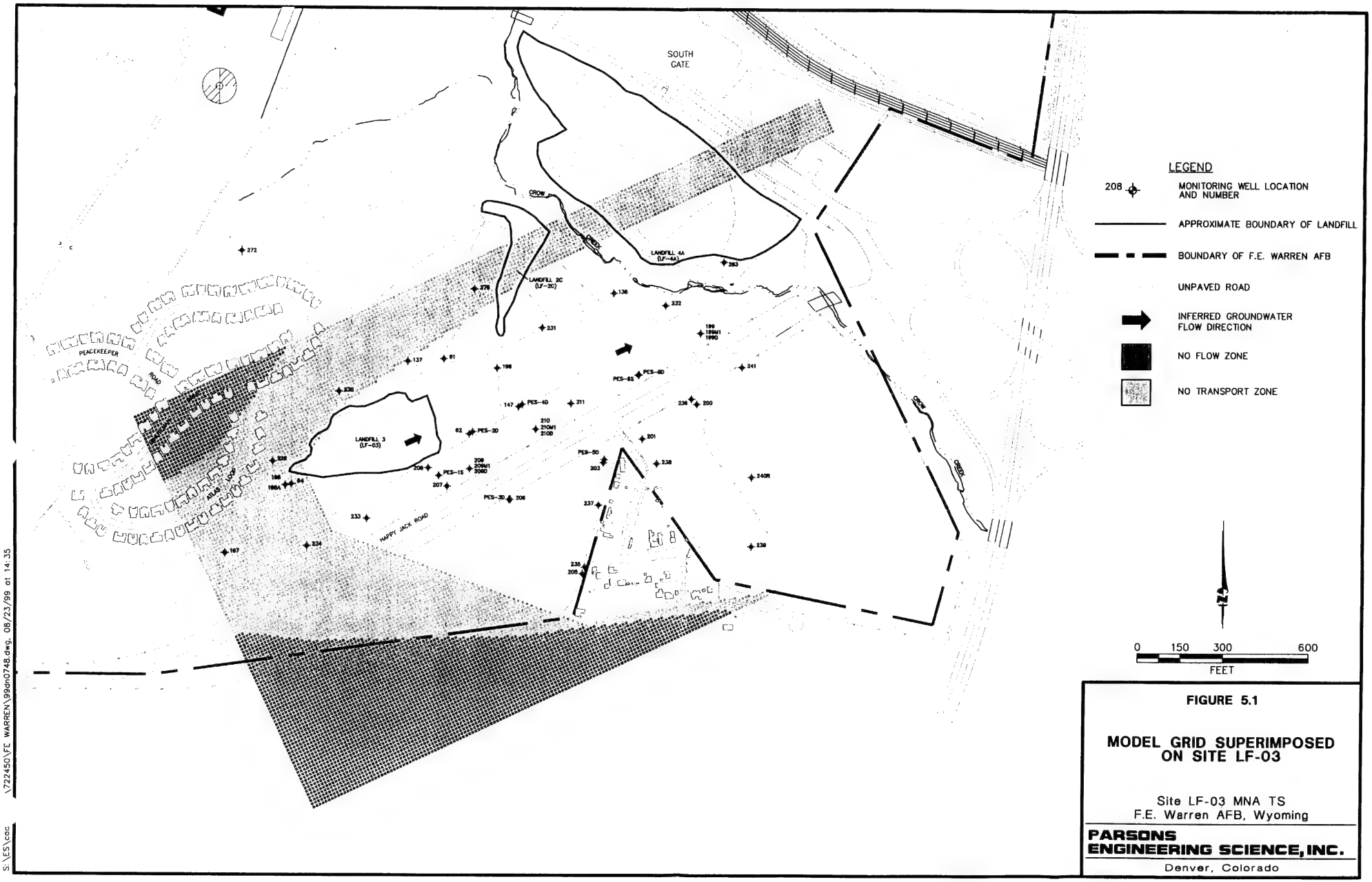

FIGURE 5.1

MODEL GRID SUPERIMPOSED ON SITE LF-03

Site LF-03 MNA TS
F.E. Warren AFB, Wyoming

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

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layering was specified to cover the known vertical extent of TCE contamination and to provide a layer separating shallow and intermediate-depth observation wells. This was accomplished by specifying saturated three layers with thickness' of 10, 15, and 15 feet from top to bottom, respectively. The top model layer (layer 1) contains monitoring wells with screened intervals at or near the water table, while the bottom layer (layer 3) contains the majority of monitoring wells screened at intermediate depths. An intermediate layer (layer 2) separates these two depth intervals. Monitoring wells with deeper screened intervals at which TCE has not been detected, are below the model's 40-foot total saturated thickness.

The top of layer 1 was defined using kriged ground surface elevation data. The layer 1 bottom was defined by kriging May 1999 shallow groundwater elevations, with 10 feet subtracted at each well. The bottoms of layers 2 and 3 were similarly specified by kriging the same water table elevations minus 25 and 40 feet, respectively. "Dummy" ground surface and water table data were used to obtain qualitatively correct kriged surfaces in zones of sparse or absent well data (particularly in the poorly characterized areas proximate and to the east of Crow Creek).

5.4.3 Groundwater Flow Model

This section presents the initial input parameters used for the groundwater flow simulations. Contaminant transport input parameters are discussed in Section 5.4.4.

5.4.3.1 Boundary Conditions

Boundary conditions describe the interaction between the system being modeled and its surroundings or, for transport models, the loading of contaminant mass into the system. Boundary conditions are used to include the effects of the system outside the area being modeled with the system being modeled, while at the same time allowing the isolation of the desired model domain from the larger system. In effect, the boundaries of the model tell the area immediately inside the boundaries what to expect from the outside world. The governing equation for saturated groundwater flow is an elliptic partial differential equation. To obtain a unique solution for the head distribution, specification of the conditions at the periphery of the system is required. Model boundary conditions are mathematical statements that specify the dependent variable (head) or the flux of water at the grid boundaries.

Three types of boundary conditions are generally used to describe groundwater flow and solute transport. Boundary conditions are referred to as specified-head type (Dirichlet), specified-flux type (Neumann), and head-dependent or mixed type (Cauchy). Table 5.1 summarizes boundary conditions for groundwater flow and solute transport.

In flow models, boundary conditions are ideally used to specify actual hydrogeologic boundaries to the system, such as a geologic feature that may bound a system or areas where properties (e.g., flux) are known and can be defined. When using a numerical flow model, hydrologic boundaries such as constant-head features (e.g., lakes, streams, etc.) or constant-flux features (e.g., groundwater divides, confining units, etc.,) should, when possible, coincide with the perimeter of the model. In areas that lack obvious hydrologic boundaries, constant-head or constant-flux boundaries can be specified at the numerical

model perimeter as long as the perimeter is far enough removed from the contaminant plume that transport calculations would not be affected by inaccuracies in the simulated boundary conditions.

TABLE 5.1
COMMON DESIGNATIONS FOR SEVERAL IMPORTANT BOUNDARY CONDITIONS
SITE LF-03 MNA TS
F.E. WARREN AFB, WYOMING

Boundary Condition	Formal Name	General Mathematical Description	
		Groundwater Flow	Contaminant Transport
Specified-Head or Specified-Concentration	Dirichlet	$H = f(x,y,z,t)$	$C = f(x,y,z,t)$
Specified-Flux	Neumann	$\frac{\partial H}{\partial n} = f(x,y,z,t)$	$\frac{\partial C}{\partial n} = f(x,y,z,t)$
Head-Dependent or Concentration-Dependent Flux (mixed-boundary condition)	Cauchy	$\frac{\partial H}{\partial n} + cH = f(x,y,z,t)$	$\frac{\partial C}{\partial n} + cC = f(x,y,z,t)$

(Modified from Franke *et al.*, 1987)

Specified-head cells were defined at the lateral periphery of the model grid for each of the three layers. The specified heads were estimated from contoured May 1999 well water table data. Except in the vicinity of Crow Creek, specified heads at the periphery were constant with depth, resulting in purely horizontal flow across the boundaries. In the top layer near Crow Creek, boundary cells with specified heads were adjusted to induce a small upward gradient near the creek. Crow Creek itself was specified as a linear feature in the top layer, with fixed heads estimated from ground surface topographic maps. The remainder of the top surface was specified as an unconfined aquifer. Due to the semi-arid climate, surface recharge was neglected except for small amounts in the landfill vicinity that served as a source of dissolved TCE. The bottom of the model grid was a zero-flux boundary. A steady-flow approach was used to simulate TCE transport, therefore all flow boundary conditions were constant through time.

5.4.3.2 Aquifer Properties

Hydraulic conductivity values typical of the site were obtained from results of slug tests performed during the TS. The calculated values are summarized in Table 3.1, and discussed in Section 3.2.2. Average hydraulic conductivities similar to those discussed in Section 3.2.2 were initially defined for large zones within the model domain. Aside from a narrow zone bordering Crow Creek in the top layer, conductivities were uniform in the vertical direction. Excluding the Crow Creek zone, only two major zones of differing conductivity were specified. The boundary separating these two zones parallels the creek

and falls approximately halfway between the creek and the landfill, and coincides with a marked change in the hydraulic gradient. On the upgradient side, hydraulic gradients are lower and hydraulic conductivity is higher, while the reverse is true downgradient of the boundary.

The effective porosity is the percentage of a rock or sediment through which fluids can travel. An effective porosity value of 20 percent was estimated for Quaternary and shallow Ogallala Formation sediments on the basis of literature values for grain size distributions observed in soil boreholes at the site (Spitz and Moreno, 1996).

5.4.3.3 Aquifer Stresses

No groundwater supply or recovery wells are currently located in the model domain. Therefore no aquifer stresses were modeled and groundwater flow was assumed to be steady state for the 39-year model calibration simulations. As pump-and-treat remedial alternatives are not anticipated, predictive transport simulations used the same steady-state flow field.

5.4.3.4 Aquifer Storage

Although steady-state groundwater flow was assumed, MT3D96 treats the input flow field calculated by MODFLOW as if it were transient. Aquifer storage properties must therefore be assigned for the solute transport model. The shallow saturated zone is modeled as an unconfined aquifer, and a specific yield of 0.20 was assigned. Specific yield is similar to effective porosity of the aquifer, because it represents the water that can drain from the aquifer material pore spaces.

5.4.4 Contaminant Transport Model

Subsequent to performing groundwater flow simulations, the model was used to simulate fate and transport of TCE. Biodegradation rates calculated in Section 4 reflect combined effects of reductive dehalogenation (source area) and aerobic oxidation. May 1999 laboratory analytical results for 27 monitoring wells were used as TCE comparison concentrations for model calibration. Table 4.4 presents dissolved TCE concentration data for May 1999, and Figure 4.6 shows the spatial distribution of dissolved TCE in May 1999. Similar TCE data at 18 wells sampled in 1993 (Table 4.1 and Figure 4.3) were used as a secondary calibration target.

5.4.4.1 Source

Transport models use boundary conditions to express the influence of contaminant sources such as mobile and residual NAPL, biodegradation of parent compounds, and dissolved mass entering through recharge, injection wells, surface water bodies, or leaking structures. Sources such as NAPL bodies may be represented as specified-concentration boundaries (limited by solubility constraints or observed maximum concentrations) or as specified-flux boundaries (for which the chemical loading rate must be known or estimated). However, in most cases, only the effects of the source are measured; the detailed source characteristics and history are typically unknown (Spitz and Moreno, 1996). The source must therefore be represented as a "black box" that

produces appropriate contaminant concentrations or fluxes at selected points in the model. The source may be misrepresented under such a scenario, but there is often little choice in the matter. Estimating contaminant flux into groundwater from NAPL is difficult and is dependent upon several parameters, most of which cannot be measured (Abriola, 1996; Feenstra and Guiguer, 1996).

Rather than using various calculations to attempt to estimate TCE partitioning from NAPL into groundwater, the "black-box" source approach was used for this application. Experience modeling contaminated sites as part of the AFCEE Natural Attenuation Initiative has suggested that this is currently the best available method for reproducing observed plumes. At LF-03, the TCE is assumed to enter groundwater dissolved in leachate over relatively large areas, through point sources due to spills or dumping, and through contact between groundwater and residual NAPL at or below the water table.

It is likely that contaminants were first introduced into groundwater at this site shortly after the opening of LF-03 in 1960. Solvents, fuels, and other liquid wastes may have been spilled or dumped, or have leaked from containers in the landfill. For the model it was assumed that contaminants first entered the groundwater in 1960, and that residual soil contamination associated with the leached or NAPL waste has acted as a continuous source. It was assumed that no new sources have been placed since the early 1990's, and that residual sources have subsequently begun to weather.

For predictive modeling after 1999, it was assumed that the source will continue to weather (lose mass) due to processes such as volatilization, dissolution, and biodegradation, and that the mass of contaminants entering groundwater will continue to decline. Past experience with the AFCEE Natural Attenuation Initiative has suggested that residual NAPL sources can weather at rates as rapid as 10 percent per year. The rate of weathering for predictive simulations was estimated as part of the calibration exercise by determining which rate was most consistent with downgradient, near-source concentrations in 1993 and 1999. It was found that a weathering rate of 7.3% per year was most consistent with observed TCE concentrations given the source configuration obtained through calibration. Thus, the model assumes that late in the calibration period and after 1999, the source loading rates decreased geometrically by 7.3 percent per year (in practice, five-year loading periods were assigned with 7.3 percent per year reductions compounded to yield a 32 percent reduction every five years).

5.4.4.2 Dispersivity

Published data summarized by Spitz and Moreno (1996) suggest that, as a rule of thumb, longitudinal dispersivity is approximately one-tenth the travel distance of the plume (from the source to the downgradient toe), which is equivalent to approximately 180 feet at LF-03 (total plume length of 1,800 feet, Figure 4.3). This was the initial value assigned to longitudinal dispersivity. The initial transverse dispersivity was estimated as one-tenth of the longitudinal dispersivity value, and vertical dispersivity was assumed to be one-hundredth of the longitudinal dispersivity (Domenico and Schwartz, 1990).

5.4.4.3 Retardation

Retardation of contaminants relative to the advective velocity of the groundwater occurs when contaminant molecules are sorbed to organic carbon, silt, or clay in the aquifer matrix. Using measured TOC concentrations in the shallow saturated zone at seven locations across the site (Table 4.2), an assumed bulk density of 1.65 kilograms per liter (kg/L), and published values of the TCE soil sorption coefficient (K_{oc}) (as listed in Wiedemeier *et al.*, 1999b), the coefficient of retardation for each contaminant was calculated. The results of these calculations are summarized in Table 5.2. The lower the assumed coefficient of retardation, the faster the TCE plume will migrate downgradient. Initially, the calculated average retardation coefficient of 1.2 for TCE was assigned to the model.

5.4.4.4 Biodegradation

As discussed in Section 4.5, a first-order decay rate of approximately 5×10^{-5} per day (day^{-1})was calculated for TCE using site-specific data. This rate was used as an initial estimate for the entire model domain.

5.5 MODEL CALIBRATION

Model calibration is an important component in the development of any numerical groundwater model. Calibration of the flow model demonstrates that the model is capable of matching hydraulic conditions observed at the site; calibration of a contaminant transport model (using the calibrated flow field as input) helps demonstrate that contaminant loading and transport conditions are being appropriately simulated. Model input and output summaries are included in Appendix F.

5.5.1 Groundwater Flow Model

Groundwater elevation data collected in May 1999 and presented on Figure 3.6 were used to calibrate the flow model. Water level elevation data from 43 monitoring wells/points were used to compare measured and simulated heads for calibration. The selected locations are listed in Appendix E.

The numerical flow model was calibrated by altering hydraulic conductivities in a trial-and-error fashion until simulated heads approximated observed field values within a prescribed accuracy. Hydraulic conductivities were varied within the limits of the observed data. As mentioned in section 5.4.3.2, three different lithology zones were defined for the model domain. The same distributions were used for the lower two layers as well, except that the narrow zone bordering Crow Creek is absent. The flow model was initially calibrated as a steady-state model; later, it was run in a transient mode to facilitate the transport solution. The steady-state calibrated heads were used as initial heads for the flow and transport simulations, during which the heads did not change significantly.

Figure 5.2 shows the calibrated water table for layer 1. Calibrated model horizontal hydraulic conductivities for the upgradient and downgradient lithology zones were 4.0 and 0.8 ft/day, respectively. As no well data were available near the creek and it was felt

TABLE 5.2
CALCULATION OF RETARDATION COEFFICIENTS
SITE LF-03 MNA TS
F.E. WARREN AFB, WYOMING

Location	Compound	K_{oc} (L/kg [a/])	Maximum Fraction Organic Carbon [b/]	Minimum Fraction Organic Carbon [b/]	Average Fraction Organic Carbon [b/]	Distribution Coefficient K_d (L/kg) Maximum [c1/]	Minimum [c2/]	Average [c3/]	Bulk Density (kg/L) [d/]	Effective Porosity [d/]	Coefficient of Retardation Maximum	Minimum	Average
Laboratory Values													
Fine Sand to Silt	PCE	209	0.00038	0.00018	0.0002733	0.080	0.037	0.057	1.65	0.20	1.66	1.30	1.47
Fine Sand to Silt	TCE	87	0.00038	0.00018	0.0002733	0.033	0.015	0.024	1.65	0.20	1.28	1.13	1.20
Fine Sand to Silt	1,1-DCE	64.6	0.00038	0.00018	0.0002733	0.025	0.011	0.018	1.65	0.20	1.20	1.09	1.15
Fine Sand to Silt	cis-1,2-DCE	49	0.00038	0.00018	0.0002733	0.019	0.009	0.013	1.65	0.20	1.15	1.07	1.11
Fine Sand to Silt	trans-1,2-DCE	36	0.00038	0.00018	0.0002733	0.014	0.006	0.010	1.65	0.20	1.11	1.05	1.08
Fine Sand to Silt	VC	2.45	0.00038	0.00018	0.0002733	0.001	0.000	0.001	1.65	0.20	1.01	1.00	1.01
Literature Values [e/]													
Fine Sand to Silt	PCE	209	0.00160	0.00053	0.001065	0.334	0.111	0.223	1.65	0.20	3.76	1.91	2.84
Fine Sand to Silt	TCE	87	0.00160	0.00053	0.001065	0.139	0.046	0.093	1.65	0.20	2.15	1.38	1.76
Fine Sand to Silt	1,1-DCE	64.6	0.00160	0.00053	0.001065	0.103	0.034	0.069	1.65	0.20	1.85	1.28	1.57
Fine Sand to Silt	cis-1,2-DCE	49	0.00160	0.00053	0.001065	0.078	0.026	0.052	1.65	0.20	1.65	1.21	1.43
Fine Sand to Silt	trans-1,2-DCE	36	0.00160	0.00053	0.001065	0.058	0.019	0.038	1.65	0.20	1.48	1.16	1.32
Fine Sand to Silt	VC	2.45	0.00160	0.00053	0.001065	0.004	0.001	0.003	1.65	0.20	1.03	1.01	1.02

[a/] From technical protocol (Wiedemeier *et al.*, 1996a)

[b/] From laboratory analyses of site soil samples

[c1/] K_d = Maximum Fraction Organic Carbon x K_{oc}

[c2/] K_d = Minimum Fraction Organic Carbon x K_{oc}

[c3/] K_d = Average Fraction Organic Carbon x K_{oc}

[d/] Estimated Value.

[e/] Literature values for fraction organic carbon (Wiedemeier *et al.*, 1998) are representative of low literature values for fine sand to silt.

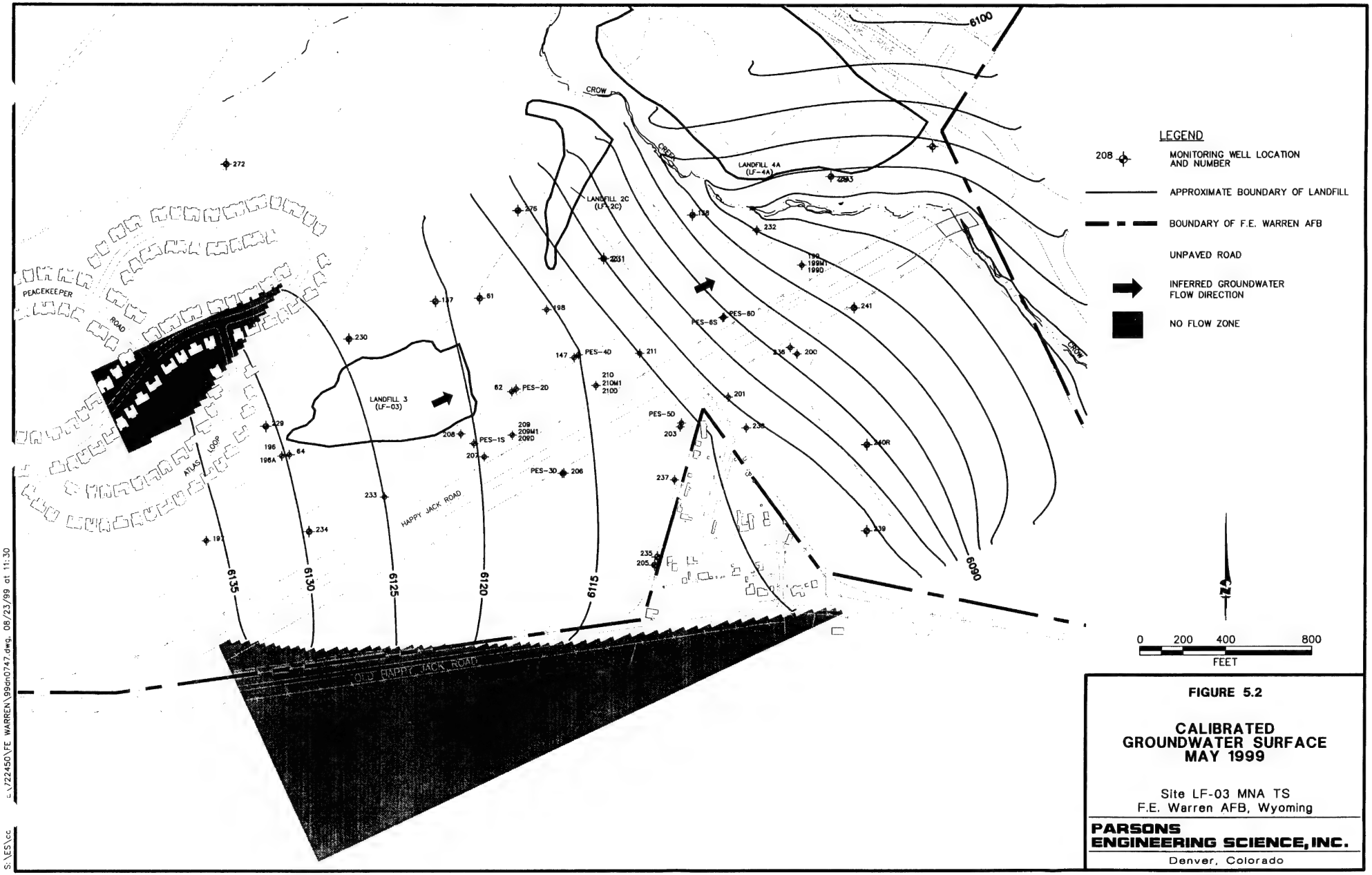

FIGURE 5.2

CALIBRATED GROUNDWATER SURFACE MAY 1999

Site LF-03 MNA TS
F.E. Warren AFB, Wyoming

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Denver, Colorado

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that sediments at the creek should be more permeable than surrounding sediments, the conductivity for the top layer Crow Creek zone was somewhat arbitrarily set to 2.0 ft/day. For all materials other than the Crow Creek sediments, the vertical anisotropy ratio was 1:10. For Crow Creek sediments the ratio was 1:1.

The root mean squared (RMS) error is commonly used to express the average difference between simulated and measured heads. RMS error is the average of the squared differences between measured and simulated heads, and can be expressed as:

$$\text{RMS}=\left[\frac{1}{n}\sum_{i=1}^{n}(h_m - h_s)_i^2\right]^{0.5}$$

where: n = the number of points where heads are being compared,

h_m = measured head value, and

h_s = simulated head value.

The RMS error between observed and calibrated values at 43 well locations was 1.7 feet, which corresponds to a calibration error of 2.7 percent (Appendix E). A plot of the measured versus simulated hydraulic heads (Appendix E) provides a qualitative method of checking the calibrated head distribution; the points should scatter randomly about the straight line (Anderson and Woessner, 1992). In general, this is the case for the LF-03 model.

In solving the groundwater flow equation, Visual MODFLOW establishes the water table surface and calculates an overall hydraulic balance that accounts for the numerical difference between flux into and out of the system. To the number of decimal places reported by Visual MODFLOW, the hydraulic mass balance for the steady-state calibrated flow model had a 0.0 percent discrepancy. This is more than adequate to accomplish the objectives of the modeling effort. According to Anderson and Woessner (1992), a mass balance error of around 1 percent is acceptable, while Konikow (1978) indicates an error of less than 0.1 percent is ideal.

5.5.2 Plume Calibration

After calibration of the final flow model, the numerical solute transport model was calibrated by altering the contaminant specified-flux rate in the source cells and the contaminant transport parameters in a trial-and-error fashion until the simulated plume approximated observed field values. For plume calibration, the model was run for a 39-year period (1960 to 1999). The transport parameters varied during plume calibration were the source-cell loading concentrations, the plume dispersivity, the TCE decay rate constant, the distribution coefficient for contaminant sorption, and effective porosity.

The dissolved TCE concentrations obtained from May 1999 laboratory analytical data from 27 monitoring wells/points were used to calibrate the contaminant transport model. Calibration sample locations and names are included in Appendix E.

5.5.2.1 Source Concentrations

The 39-year time period was divided into five-year increments and the TCE mass flux history at each source cell was specified as a step function, with constant flux specified for any given period. Mass flux was specified for top layer blocks by assigning a low, nominal recharge rate and a different recharge concentration for each specified source zone. Three separate source zones near the southern border of LF-03 were necessary to achieve an acceptable model calibration. The model grid blocks included in these source zones are depicted in Figure 5.3. Table 5.3 summarizes the simulated TCE mass flux histories for the three source zones.

The first zone is a large area where relatively low per-cell TCE fluxes were specified for the entire 39-year calibration period. Flux from this zone is perhaps due to landfill leachate formation, and decreases in flux in the latter years of the calibration may be due to source depletion. Flux from this zone reproduced an excellent match to the overall plume shape and extent, but some of the near-source plume "hotspots" were still unaccounted for.

The second and third zones (Figure 5.3) represented pulse-sources of higher per-cell mass flux than the first zone. These pulses were possibly due to NAPL spills, leaks, or dumping, or convergence of relatively concentrated leachate through preferred pathways. Field evidence suggests that the second pulse-source zone is situated somewhere between three closely spaced upgradient wells (208, PES-1S, and 207) and well 209, approximately 160 feet downgradient of well PES-1D. In both 1993 and 1999, the highest detected concentrations of TCE were downgradient of wells 208, PES-1S, and 207, but at or upgradient of well 209.

A third pulse-source zone is located at the eastern edge of the landfill, and was included to address relatively low concentrations of TCE along the northern edge of the plume. Specifically, May 1999 data indicate that TCE concentrations were higher at well 147 than at well 62, which lie on the same flowpath but for which well 62 is closer to the source. This situation was attributed to an earlier pulse of TCE released in the vicinity of the third source zone.

As seen in Table 5.3, loading rates for zone 1 tail off at the previously mentioned 7.3 percent per year rate, or 32 percent over 5 years. For the pulse zones, rates drop much more rapidly. For both zones at which loading still exists at the end of calibration (zones 1 and 2), future loadings for a no-action scenario were reduced by 7.3 percent per year.

5.5.2.2 Dispersivity

The initial longitudinal dispersivity of 180 feet produced a simulated plume far longer and wider than that observed in 1999. This value was gradually decreased to 25 feet. Calibrated lateral-to-longitudinal and vertical-to-longitudinal dispersivity ratios were 0.10

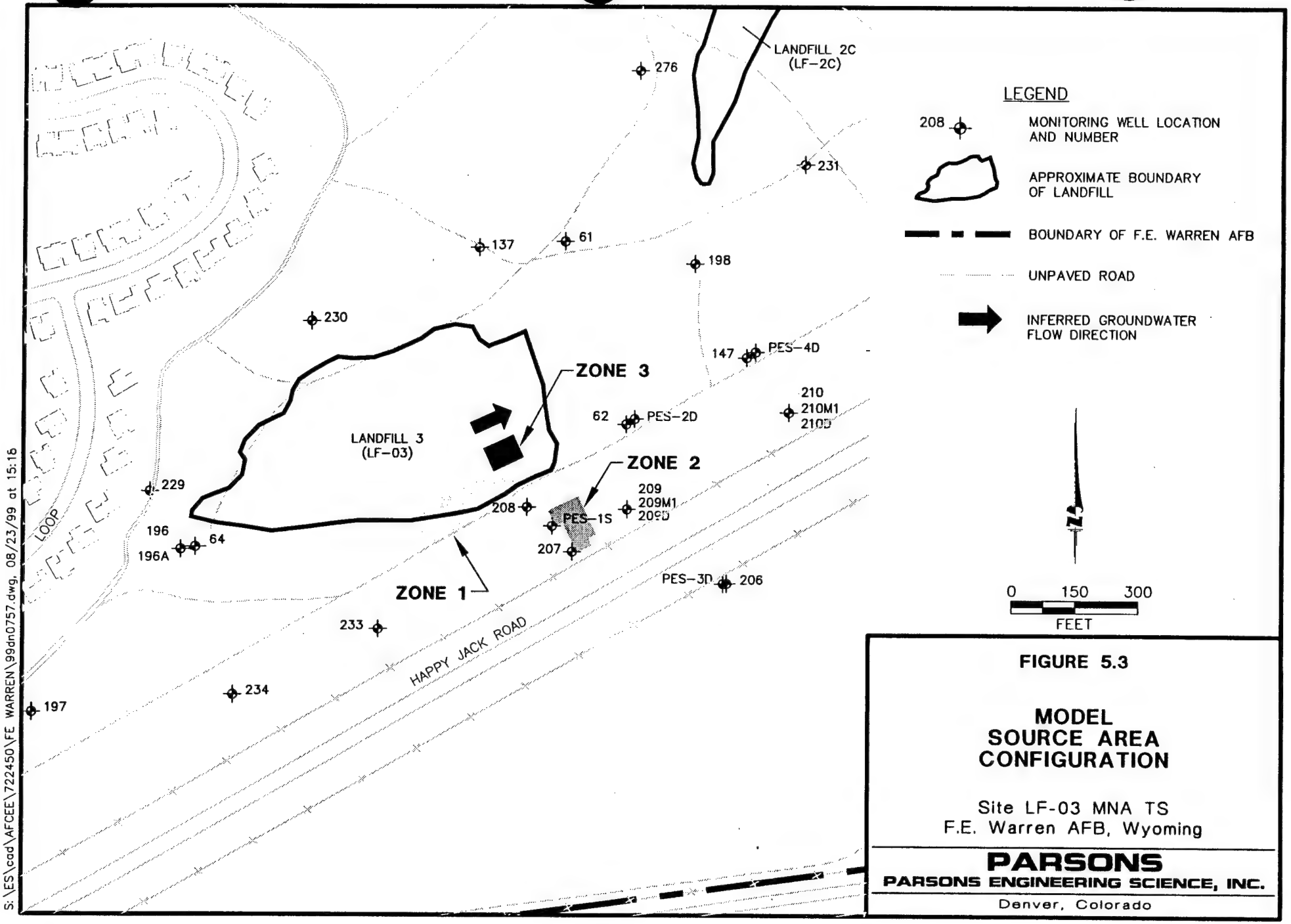

FIGURE 5.3

MODEL SOURCE AREA CONFIGURATION

Site LF-03 MNA TS
F.E. Warren AFB, Wyoming

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Denver, Colorado

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TABLE 5.3
TCE MASS LOADING BY SOURCE ZONE
CALIBRATED MODEL
SITE LF-03 MNA TS
F.E. WARREN AFB, WYOMING

Time Period	Source Zone 1 78 Cells; 31,200 ft²		Source Zone 2 19 Cells; 7,600 ft²		Source Zone 3 12 Cells; 4,800 ft²		Cumulative TCE Loaded (kg)
	TCE Flux per Cell (kg/yr)	Total TCE Flux (kg/yr)	TCE Flux per Cell (kg/yr)	Total TCE Flux (kg/yr)	TCE Flux per Cell (kg/yr)	Total TCE Flux (kg/yr)	
1960-65	0.0028	0.2209	0	0	0	0	1.104
1965-70	0.0028	0.2209	0	0	0	0	2.209
1970-75	0.0028	0.2209	0	0	0	0	3.313
1975-80	0.0019	0.1516	0.0094	0.1793	0	0	4.966
1980-85	0.0013	0.1034	0.0047	0.0897	0.0094	0.1133	6.497
1985-90	0.0009	0.0708	0.0024	0.0448	0	0	7.075
1990-95	0.0006	0.0484	0.0094	0.1793	0	0	8.214
1995-99	0.0004	0.0331	0.0047	0.0897	0	0	8.705

and 0.035, respectively. It was not necessary to vary any of the dispersivity parameters by zone to obtain acceptable calibration results.

5.5.2.3 TCE Decay Rates

The decay rate was varied during plume calibration, and was important in controlling plume length and concentration distributions. When simulating degradation of chlorinated solvents, it is often necessary to define zones of varying decay rate. For example, higher rates in the near-source and plume core area are typically reflective of Type 1 behavior, while downplume environments may exhibit more aerobic Type 3 behavior and have lower rates. It should be noted that zones of degradation actually evolve through time, whereas this approach treats them as static. For TCE transport simulation at the LF-03 site, it was found that zones of different degradation rate were not necessary to obtain acceptable calibration results. The degradation rate obtained at

the end of the calibration procedure was 7.6×10^{-5} day^{-1} (half-life of 25 years). Because of the limitations of transport codes to simulate complex biodegradation reactions, the rate obtained from the calibration process should be viewed as a spatial and temporal average over the calibration period.

5.5.2.4 Sorption

The retardation coefficient accounts for sorption and is calculated as

$$R = 1 + \frac{\rho_B K_D}{n_{EFF}}$$

where

ρ_B = soil bulk density (mass/volume)

K_D = distribution coefficient (volume/mass)

n_{EFF} = effective porosity

During plume calibration, the retardation coefficient was varied, but the final calibrated value was left at the initial estimate of 1.2 throughout the model domain. This value was based on the average soil TOC concentration measured in May 1999 (Table 4.2), and was calculated using a bulk density of 1.65 kg/L, a distribution coefficient of 0.024 liters per kilogram (L/kg), and an effective porosity of 0.2. A higher retardation value of 1.5, when combined with a slightly lower degradation rate and higher vertical dispersivity, resulted in a slightly better calibration to the 1999 data. The 1.2 value was favored for several reasons: the calibration improvement with the higher value was only marginal; the range of TOC measurements was rather narrow and the 1.5 value implied generally higher TOC than was observed; the 1.2 value yielded a better fit to the available 1993 data; and use of the 1.2 value was conservative for predictive simulations.

It should be noted that sorption of any constituent can vary substantially among soils with similar organic content. Domenico and Schwartz (1990) and Pankow and Cherry (1996) note that sorption of organic compounds estimated on the basis of TOC alone is often underestimated because the role of sorption onto clays and other mineral surfaces is ignored. In addition, Ball and Roberts (1991) note that partitioning coefficients also can be underestimated if they are based on laboratory studies performed on a short time scale (days to months). In reality, most field-scale situations (such as LF-03) involve time scales of tens of years.

5.5.2.5 Effective Porosity

The initial effective porosity estimate of 0.2 was found to give acceptable calibration results. This value was assigned to the entire model domain.

5.5.2.6 Transport Calibration Results

The calibrated layer 1 TCE plume produced by the model (Figure 5.4) is quite similar to the observed May 1999 plume (Figure 4.6). Overall, the concentrations and distribution of TCE for the calibrated plume are very good. The RMS error of prediction for the 27 observations wells was 6.7 µg/L, or 7.2 percent. A plot of predicted versus measured TCE concentrations is included in Appendix A.

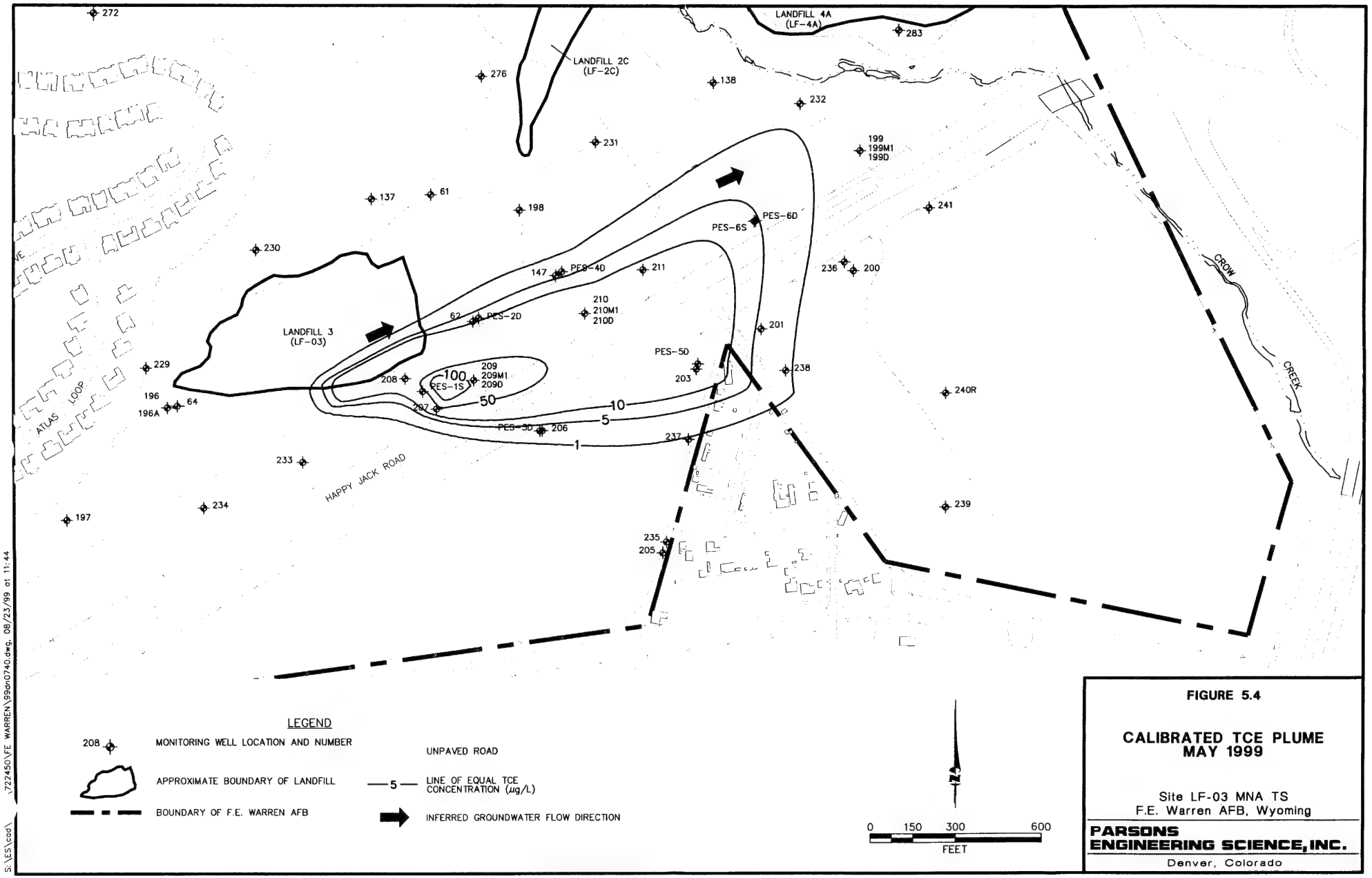

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FIGURE 5.4

CALIBRATED TCE PLUME MAY 1999

Site LF-03 MNA TS
F.E. Warren AFB, Wyoming

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Denver, Colorado

In general, simulated TCE concentrations are a relatively close match to measured concentrations. As can be seen from Figure 5.4, the model is conservative in that it slightly overpredicts the majority of concentrations. The only significant underpredictions are at well 209M1 (76.2 µg/L measured versus 52.5 µg/L predicted), well PES-4D (12.3 µg/L measured versus 3.9 µg/L predicted), well 147 (10.3 µg/L measured versus 4.0 µg/L predicted), and well PES-6S (11.0 µg/L measured versus 5.5 µg/L predicted). The latter three are at the northern edge of the plume where concentration gradients are high. Well 209M1 is immediately downgradient from the second pulse-source zone and is screened deeper than well 209, at which the highest concentration of TCE was detected in 1999. A better match could have been obtained at well 209M1 with greater vertical dispersivity, but only at the expense of a poorer overall fit to the downgradient TCE plume. Multiple dispersivity zones could have been employed to address this discrepancy, but additional model complexity was deemed unnecessary in light of the relatively small calibration residuals.

Given the slight overprediction of concentrations at many wells, it appears that adequate TCE mass was introduced to the system. Areas enclosed by isopleths appear to be very similar for simulated and measured TCE concentrations. This is important to note because the introduction of sufficient contaminant mass results in conservative predictions of downgradient receptor impacts and plume persistence.

The calibrated layer 1 TCE plume produced by the model for 1993 is shown on Figure 5.5. Overall, the concentrations and distribution of TCE for the simulated 1993 plume is also very good, and provides a secondary plume for comparison.

5.6 SENSITIVITY ANALYSIS

The purpose of a sensitivity analysis is to determine the effect of varying model input parameters on model output. The sensitivity analysis was conducted by varying sorption (i.e., the distribution coefficient K_d), the first-order decay rate, dispersivity, hydraulic conductivity, and effective porosity.

To perform the sensitivity analyses, the calibrated model was adjusted by systematically changing the aforementioned parameters individually, and then comparing the new simulations to the results of the calibrated model. The models were run for a 39-year period, just as the calibrated model was, so that the independent effect of each variable could be assessed. Ten sensitivity runs of the calibrated model were made, with the following variations:

1. All hydraulic conductivities doubled;

2. All hydraulic conductivities halved;

3. Distribution coefficient doubled, which resulted in retardation coefficient set to 1.4;

4. Distribution coefficient halved, which resulted in retardation coefficient set to 1.1;

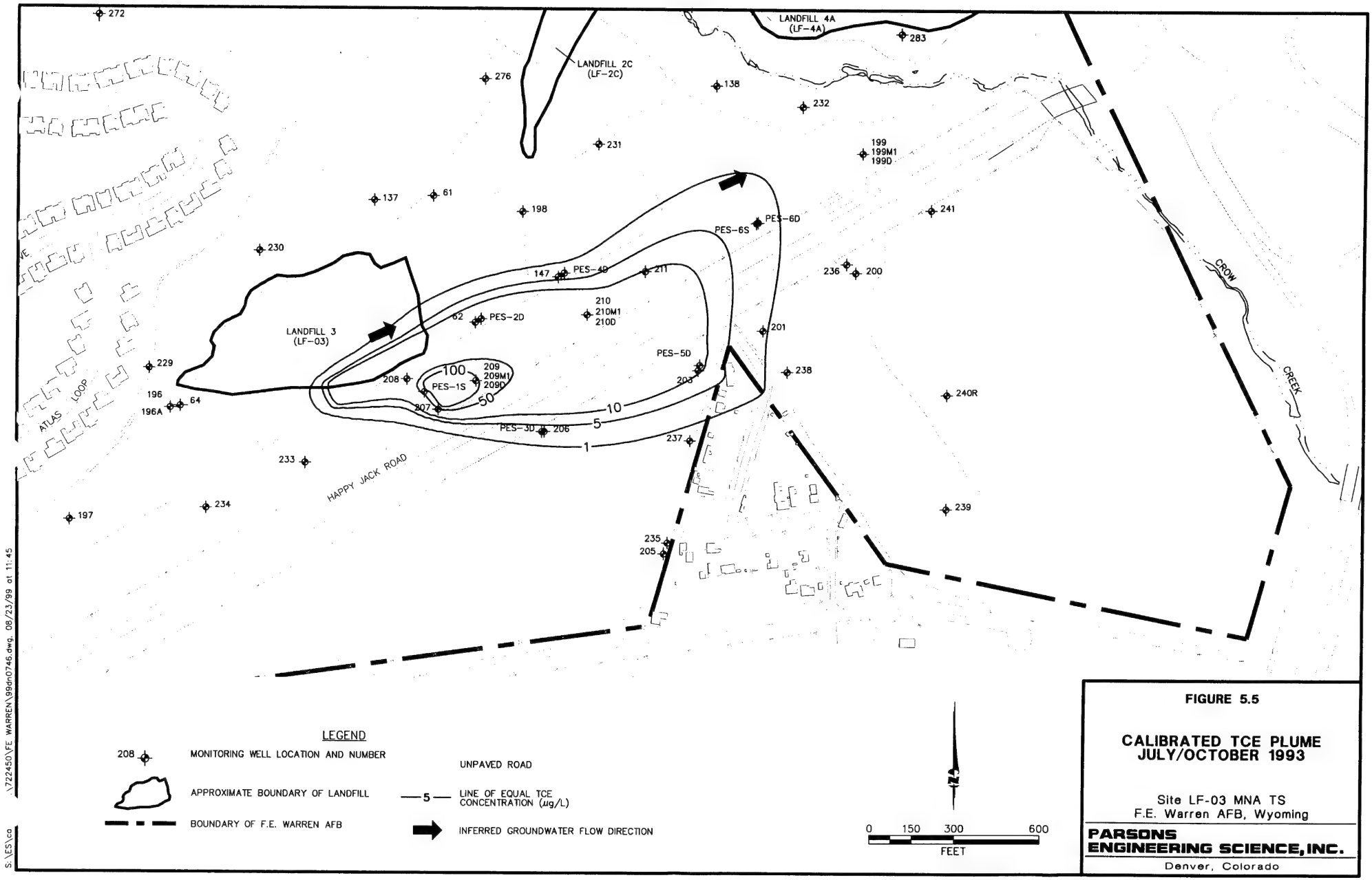

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FIGURE 5.5

CALIBRATED TCE PLUME JULY/OCTOBER 1993

Site LF-03 MNA TS
F.E. Warren AFB, Wyoming

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5. Longitudinal dispersivity doubled;

6. Longitudinal dispersivity halved;

7. Decay rates doubled;

8. Decay rates halved;

9. Effective porosity doubled;

10. Effective porosity halved;

The results of the sensitivity analyses are discussed in the following subsections and summarized in Table 5.4. As described in the following paragraphs, the parameter modifications listed above generally caused substantial changes in the resulting plumes. The plume shape and distribution are most sensitive to change in hydraulic conductivity and least sensitive to change in the distribution coefficient.

5.6.1 Sensitivity to Variations in Hydraulic Conductivity

Hydraulic conductivity is an important aquifer characteristic that represents the ability of the water-bearing strata to transmit groundwater. An accurate estimate of hydraulic conductivity is important to help quantify advective groundwater flow velocity and to define the flushing potential of the aquifer. As a result, models used to estimate contaminant transport are particularly sensitive to variations in hydraulic conductivity. Lower values of hydraulic conductivity result in a slower-moving plume. Higher values of hydraulic conductivity result in a faster-moving plume. The effects of varying hydraulic conductivity are summarized in columns A and B of Table 5.4.

Uniformly increasing the hydraulic conductivity by a factor of two significantly increased the extent of the plume so that the 10-µg/L isopleth reached approximately 520 feet further downstream than for the calibrated case. Simulated concentrations far downgradient of the source area and at the plume margins were much higher than for the calibrated model. In contrast, decreasing the hydraulic conductivity by a factor of two slowed overall plume migration, and resulted in a much shorter plume with contaminant mass occupying a much smaller area.

5.6.2 Sensitivity to Variations in the Distribution Coefficient

The effects of varying the distribution coefficient (K_d) are summarized in columns C and D of Table 5.3. Doubling K_d increased the retardation factor R to 1.4. This increase produced a slightly shorter and narrower plume, with concentrations outside of the near-source area slightly below those in the calibrated model. This reflects the increased mass of TCE sorbed to the soil matrix. This sensitivity run actually produced a slightly lower RMS error than for the calibrated case. However, for reasons summarized is Section 5.5.2.4, use of R = 1.2 was felt to produce a better overall calibration.

TABLE 5.4

SUMMARY OF SENSITIVITY ANALYSIS RESULTS

SITE LF-03 MNA TS

F.E. WARREN AFB, WYOMING

Well	Observed Concentration (ppb)	Calibrated Concentration (ppb)	A	B	C	D	E	F	G	H	I	J
198	0	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00
199	0	0.09	7.57	0.00	0.02	0.21	0.30	0.02	0.03	0.15	0.00	10.73
199M1	0	0.09	7.64	0.00	0.02	0.21	0.31	0.02	0.03	0.16	0.00	10.86
201	0	4.16	9.59	0.00	1.94	5.78	5.00	3.34	1.81	6.33	0.00	19.57
232	0	0.54	5.98	0.00	0.16	0.93	0.93	0.27	0.20	0.88	0.00	10.02
233	0	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
236	0	0.17	6.01	0.00	0.04	0.34	0.47	0.06	0.06	0.28	0.00	9.06
237	0	0.74	0.66	0.00	0.44	0.91	1.22	0.53	0.36	1.06	0.00	1.41
62	0	9.15	2.90	40.21	10.77	8.53	10.04	9.50	6.90	10.69	19.30	6.01
PES-3D	0	2.50	1.90	2.47	2.40	2.56	4.38	1.14	1.64	3.11	1.41	3.64
PES-6D	0	4.89	13.53	0.00	2.32	6.74	5.14	4.04	1.92	7.79	0.01	24.95
238	1.1	1.38	4.45	0.00	0.57	2.03	2.07	0.90	0.59	2.11	0.00	9.03
206	2.6	2.25	1.70	2.22	2.13	2.33	3.41	1.80	1.52	2.78	1.25	3.28
PES-5D	3.3	18.51	11.24	0.57	13.71	20.65	15.53	18.19	9.33	26.30	0.53	22.70
PES-2D	4.3	5.98	1.54	21.92	7.23	5.45	8.97	2.83	4.20	7.23	10.99	3.24
211	7.5	13.52	7.51	2.73	11.15	14.73	12.45	14.95	6.85	19.17	1.92	17.26
147	10.3	4.04	0.57	2.15	3.95	3.96	5.12	3.84	2.51	5.17	1.32	1.52
PES-6S	11	5.48	13.53	0.01	2.72	7.41	5.56	5.18	2.18	8.70	0.01	25.10
PES-4D	12.3	3.90	0.58	1.63	3.64	3.90	5.13	2.51	2.40	5.00	1.01	1.57
203	12.8	18.29	10.92	0.67	13.83	20.22	14.85	23.25	9.38	25.79	0.61	21.67
210M1	18.3	21.77	6.34	18.76	21.40	21.60	19.97	18.95	13.05	28.40	10.89	13.85
208	23	19.68	8.74	49.98	20.55	19.39	19.47	24.33	17.46	21.04	24.40	17.70
210	26.7	24.31	7.20	23.05	24.22	24.00	20.20	32.47	14.75	31.56	13.22	15.58
207	33.1	29.23	13.82	62.67	29.84	29.03	30.57	23.60	27.36	30.38	31.32	27.76
PES-1S	33.9	39.19	18.38	89.15	40.18	38.86	43.69	31.83	36.39	40.89	44.11	36.95
209M1	76.2	52.49	21.92	106.18	54.51	51.70	48.09	49.23	45.22	57.12	53.96	45.02
209	93.1	95.41	41.54	207.07	99.47	93.99	66.06	135.26	85.04	101.93	104.41	84.27
RMS Error (ppb)		6.70	16.90	29.90	6.18	7.17	8.95	11.08	7.72	8.13	8.40	11.77

Column: A : Hydraulic Conductivity x 2.
B: Hydraulic Conductivity ÷ 2.
C: Kd x 2, Retardation = 1.4.
D: Kd ÷ 2, Retardation = 1.1.
E: Dispersivity x 2.
F: Dispersivity ÷ 2.
G: Decay Rate x 2.
H: Decay Rate ÷ 2.
I: Effective Porosity x 2.
J: Effective Porosity ÷ 2.

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Uniformly halving K_d resulted in a retardation factor of 1.1. This caused a slight increase in the length and width of the TCE plume and slightly increased TCE concentrations in the downgradient and peripheral areas of the plume.

5.6.3 Sensitivity to Variations in Dispersivity

The effects of varying dispersivity are summarized in columns E and F of Table 5.4. Longitudinal, transverse, and vertical dispersivity were all varied for this analysis, as ratios of longitudinal-to-transverse dispersivity and longitudinal-to-vertical dispersivity were kept at their calibrated values. Doubling and halving longitudinal dispersivity then resulted in doubled and halved transverse components of dispersivity.

Doubling the dispersivity components lowered peak TCE concentrations and spread more of the contaminant to the margins of the plume. The result was a plume with a slightly larger footprint, lower peak values, and slightly smaller gradients. Halving the dispersivity components had the opposite effect, resulting in a slightly smaller plume with higher peak concentrations, lower marginal concentrations, and slightly steeper gradients.

5.6.4 Sensitivity to Variations in the Decay Rate Constant

The effects of varying the first-order TCE decay rate are summarized in columns G and H of Table 5.4. Doubling the decay rate resulted in more rapid degradation of dissolved contaminants, producing a smaller plume with lower concentrations everywhere outside the source. Uniformly halving the degradation rate resulted in a slightly larger plume with higher concentrations outside the source area.

5.6.5 Sensitivity to Variations in Effective Porosity

The results of doubling and halving effective porosity are summarized in columns I and J of Table 5.4. Doubling effective porosity halved the interstitial flow velocity and resulted in much slower transport. With effectively more groundwater water available to the aquifer system, dilution of the source mass increased, and concentrations were lower than calibrated values at locations downgradient from the source. The opposite effect resulted from halving the effective porosity. Transport velocities increased and dilution diminished, yielding a much larger plume with higher concentrations downgradient of the source area.

5.6.6 Summary of Sensitivity Analysis Results

The results of the sensitivity analysis show that, compared to the calibrated model, all parameter variations except one caused a degradation in the goodness-of-fit between predictions and measurements. As previously mentioned, doubling the distribution coefficient (R = 1.4) actually resulted in a slight decrease in RMS error (from 6.7 µg/L to 6.18 µg/L). However, use of a retardation factor of 1.2 was more consistent with 1999 soil TOC data, provided a better transport calibration for the measure 1993 TCE plume (Figure 4.3), and was more conservative for predictive simulations.

Based on the sensitivity analysis, transport parameters can be ordered from most to least significant as follows: hydraulic conductivity, effective porosity, dispersivity, degradation rate, and distribution coefficient. More specifically, the parameter variations can be ranked according to the degree of deviation from the calibrated "fit" they cause. From the greatest deviation to the least, these are

1. Doubling hydraulic conductivity
2. Halving hydraulic conductivity
3. Halving effective porosity
4. Halving dispersivity
5. Doubling dispersivity
6. Doubling effective porosity
7. Halving decay rate constant
8. Doubling decay rate constant
9. Doubling distribution coefficient
10. Halving distribution coefficient

It should be noted that typical percentage variations in field-measured values of these parameters are site-specific. For example, at a particular site effective porosity measurements may vary from the mean by less than a factor of two, while the distribution coefficient may vary over orders of magnitude. In this case, a model would be more sensitive to "typical" variations in distribution coefficient than to "typical" variations in effective porosity, even if, for the same percentage change, the model were determined to be more sensitive to effective porosity.

5.7 DISCUSSION OF THE MODEL AND MODEL UNCERTAINTIES

Before discussing model predictions in Section 6, some points about the model should be emphasized. Most notably, the hydrogeologic system modeled is complex but the model itself is relatively simple, using temporally and spatially constant values for most of the flow and transport parameters. This is due to the fact that greater complexity was not necessary to achieve an acceptable calibration, and also to the fact that in many areas the relevant properties and parameters are not well defined. Additional model complexity has disadvantages; most notably drawn out calibration procedures, non-uniqueness of calibration results, and loss of clarity. It was judged that marginal improvements in an already good calibration were not worth the disadvantages of additional complexity. Very good calibration results have been obtained, indicating that a proper balance was obtained between model complexity, required model output, and available input data.

Given the underlying conceptual model of TCE sources in the LF-03 vicinity, the calibration exercise has yielded a useful tool for evaluation of future TCE transport under

different remedial alternatives. However, significant uncertainty with source history and characterization leave open the possibility that alternative source models may explain the TCE plume as well or better.

SECTION 6

COMPARATIVE ANALYSIS OF REMEDIAL ALTERNATIVES

This section presents the development and comparative analysis of remedial alternatives for contaminated groundwater at Site LF-03. The intent of this evaluation is to determine if MNA of groundwater is an appropriate and cost-effective remedial approach to consider when developing final remedial strategies for the study area, especially when combined with other remedial technologies.

Section 6.1 presents the criteria used to evaluate groundwater remedial alternatives. Section 6.2 discusses the development of remedial alternatives considered as part of this project. Section 6.3 provides a brief description of each of these remedial alternatives, and Section 6.4 provides a more detailed analysis of the remedial alternatives using the defined remedial alternative evaluation criteria. Results of this evaluation process are summarized in Section 6.5.

6.1 REMEDIAL ALTERNATIVE EVALUATION CRITERIA

The evaluation criteria used to identify appropriate remedial alternatives for groundwater contamination at the site were evaluated on the basis of (1) long-term effectiveness and permanence, (2) technical and administrative implementability, and (3) relative cost. The following sections briefly describe the scope and purpose of each evaluation criterion. This report focuses on the potential use of MNA to reduce dissolved chlorinated solvent concentrations in groundwater to below MCLs.

6.1.1 Long-Term Effectiveness and Permanence

Each remedial alternative (which can be a combination of remedial approaches such as MNA and institutional controls) was analyzed to determine how effectively it would minimize groundwater plume expansion so groundwater quality standards can be achieved at a downgradient sentry well or POC. The expected technical effectiveness based on case histories from other sites with similar conditions also is evaluated. The ability to minimize potential impacts on surrounding facilities and operations is considered. Also, the ability of each remedial alternative to protect both current and potential future receptors from potential risks associated with potentially completed exposure pathways is qualitatively assessed. The evaluation criterion also include permanence and the ability to reduce contaminant mass, toxicity, and volume. Long-term reliability for providing continued protection, including an assessment of potential technology failure and potential threats resulting from such a failure are also evaluated.

6.1.2 Implementability

The technical implementability of each remedial technology or remedial alternative was evaluated in terms of technical feasibility and availability. Potential shortcomings and difficulties in construction, operations, and monitoring are presented and weighed against perceived benefits. Requirements for any post-implementation site controls such as LTM and land use restrictions are described. Details on administrative feasibility in terms of the likelihood of public acceptance and the ability to obtain necessary approvals are discussed.

6.1.3 Cost

The total cost of each remedial alternative was estimated for relative comparison. Estimates of capital costs and operating and post-implementation costs for site monitoring and controls are included. An annual inflation rate of four percent was assumed in calculations for total cost over the estimated time-span of the remedial alternative.

6.2 FACTORS INFLUENCING ALTERNATIVES DEVELOPMENT

Several factors were considered during the identification and screening of remedial technologies for addressing groundwater contamination at the site. Factors considered included the objectives of the AFCEE natural attenuation demonstration program; contaminant, groundwater, and soil properties; current and future land uses; and potential receptors and exposure pathways. The following section briefly describes each of these factors and how they were used to narrow the list of potentially applicable remedial technologies.

6.2.1 Program Objectives

The intent of the RNA demonstration program sponsored by AFCEE is to develop a systematic process for scientifically investigating and documenting natural subsurface attenuation processes that can be factored into overall site remediation plans. The objective of this program and the specific demonstration at F.E. Warren AFB is to provide solid evidence of natural attenuation of dissolved chlorinated solvents so that this information can be used to develop an effective groundwater remediation strategy. A secondary goal of this multi-site initiative is to provide a series of regional case studies, which demonstrate natural processes of contaminant degradation can often reduce contaminant concentrations in groundwater to below acceptable cleanup standards before completion of potential receptor exposure pathways.

Because the objective of this program is to study natural processes in the saturated zone rather than all contaminated media (e.g., soil, soil gas, etc.), technologies have been evaluated based primarily on their potential impact to shallow groundwater and phreatic soils. Technologies that can reduce vadose zone contamination and partitioning of contaminants into groundwater also were evaluated. Many of the source removal technologies evaluated in this section will also reduce soil and soil gas contamination, but it is important to emphasize that the remedial alternatives developed in this document are

not intended to remediate all contaminated media. Additional program objectives set forth by AFCEE include cost effectiveness and waste minimization.

6.2.2 Contaminant Properties

Site-related groundwater contaminants exceeding USEPA MCLs and considered for remediation as part of this demonstration are TCE and *cis*-1,2-DCE. The primary sources of contamination at LF-03 are likely waste disposal and potential spills or dumping of waste in or near the landfill; however, the exact location and nature of these sources is unknown. The physiochemical characteristics of the individual compounds will greatly influence the effectiveness and selection of a remedial technology.

TCE was used as the target compound for remediation at LF-03. The summary of biodegradation rates in Table 4.8 by the method of Buscheck and Alcantar (1995) indicates that the half-life transformation rate of TCE to daughter products of 37 years is approximately twice the 17 year half-life transformation rate of *cis*-1,2-DCE. The transformation rate of total chlorinated ethenes to daughter product (half-life of 27 years) is approximately the average of the halve-lives for TCE and *cis*-1,2-DCE.

The maximum concentration of *cis*-1,2-DCE (129 µg/L) coincides with the maximum concentration of TCE (93 µg/L) at monitoring well location 209. The relatively low MCL for TCE (5 µg/L) relative to *cis*-1,2-DCE (70 µg/L), and the longer half-life for TCE, supports its use as a surrogate for all CAH compounds at this site during the remedial alternative evaluation process. Modeling of TCE fate and transport (Section 5) also allows for comparative modeling of selected remedial alternatives.

TCE, and *cis*-1,2-DCE are generally volatile, relatively soluble in water, and do not adsorb strongly to soil particles. These characteristics allow the CAHs to leach readily from NAPL and contaminated soil into groundwater and to migrate as dissolved contamination (Lyman *et al.*, 1992). As discussed in Section 4.1, these CAHs are amenable to *in situ* degradation by both biotic and abiotic mechanisms under certain geochemical conditions.

TCE is moderately volatile, with a vapor pressure ranging from 69 millimeters of mercury (mm Hg) to 74 mm Hg at 25°C (Mackay and Shiu, 1981; Klopffer *et al.*, 1988; Howard, 1990). Henry's Law Constants reported for TCE range from 0.0086 to 0.0102 atm-m^3/mol at 25°C (Ashworth *et al.*, 1988; Dewulf *et al.*, 1995). The solubility of pure TCE in water at 20°C has been reported to be 1,100 mg/L (Pearson and McConnell, 1975). TCE biodegradation products vary according to the prevailing groundwater geochemistry and are described in Section 4.1.

On the basis of these physiochemical characteristics, natural attenuation, land use controls, soil excavation, soil vapor extraction, air sparging, and groundwater extraction and treatment could potentially be effective options for collecting, destroying, and/or treating dissolved CAHs at Site LF-03. In addition, *in situ* degradation of CAHs via permeable reaction walls (e.g., iron filings trenched) or injection of a carbon source (electron donor) to induce reductive dehalogenation are developing technologies that hold promise for treatment of CAHs dissolved in groundwater. Some of these options are

considered less desirable after considering site-specific conditions (Section 6.2.3) and program objectives (Section 6.2.1).

6.2.3 Site-Specific Conditions

Three general categories of site-specific characteristics were considered when identifying remedial approaches for comparative evaluation. The first category was physical characteristics such as groundwater depth, hydraulic conductivity, hydraulic gradient, flow direction, and soil type. The second category was the site geochemistry, or how the site contaminants are interacting with electron acceptors, microorganisms, and other site contaminants. Both of these categories influence the types of remedial technologies most appropriate for the site. The third category involved assumptions about future land use and potential receptor exposure pathways. Each of these site-specific characteristics has influenced the development of remedial alternatives included in the comparative evaluation.

6.2.3.1 Physical Characteristics

Site geology and hydrogeology have a profound effect on the transport of contaminants and the effectiveness and scope of required remedial technologies at a given site. Hydraulic conductivity is perhaps the most important aquifer parameter governing groundwater flow and contaminant transport in the subsurface. The velocity of the groundwater and dissolved contamination is directly related to the hydraulic conductivity of the saturated zone. The estimated advective groundwater velocity at LF-03 ranges over two orders of magnitude from 1.1 ft/yr to 163 ft/yr, and averages 6.9 ft/yr (Table 3.1).

Although the relatively low hydraulic conductivity of the study area may limit plume expansion and migration, this same characteristic also may limit the effectiveness of remedial technologies such as groundwater extraction and air sparging. For example, it should be more expensive and time-consuming to capture and treat a contaminant plume using a network of extraction wells in an area of low hydraulic conductivity, because each well would envelope a smaller area of influence and sustain a lower flow rate.

Like hydraulic conductivity, the organic carbon content of native phreatic zone soils can influence the effectiveness of remedial alternatives. Soil TOC values greater than 0.01 percent are typically sufficient to cause contaminant retardation due to sorption. The difference between contaminant and groundwater velocity increases the effectiveness of biodegradation in the source area because there are fresh electron acceptors flowing past the slower moving dissolved contaminant mass. However, soils in the study area have a relatively low organic carbon content of approximately 0.027 percent (Table 4.2). Therefore, the soils at LF-03 have a correspondingly low sorptive potential.

6.2.3.2 Geochemical Characteristics

To satisfy the requirements of indigenous microbial activity and MNA, the aquifer also must provide an adequate and available carbon or energy source (e.g., fuel hydrocarbon contamination or natural carbon), electron acceptors, essential nutrients, and proper ranges of pH, temperature, and redox potential. Data collected as part of this TS

(Sections 3 and 4) indicate the immediate LF-03 source area contains limited carbon/energy sources to support reductive dehalogenation of CAH contamination by indigenous microorganisms. Dissolved oxygen, nitrate, ferric iron, sulfate, and carbon dioxide represent sources of significant electron acceptor capacity for the biodegradation of organic compounds at LF-03.

The pH in groundwater ranged between 6.83 and 8.14 standard units in May 1999, which is approximate to the optimal range for biodegradation of 6 to 8 standard pH units (Wiedemeier *et al.*, 1995). Redox potentials ranged from 30 to 276 mV in May 1999 (Figures 4.12 and 4.13), and suggest a groundwater environment that is primarily oxidizing, but also mildly reducing in the vicinity of wells PES-1S and PES-6S. The redox potentials at the site suggest that aerobic biodegradation, nitrate reduction, and manganese reduction could reduce contaminant concentrations in groundwater. Groundwater data presented in Section 4 support the conclusion that aerobic and anaerobic processes may have reduced low-level fuel hydrocarbon contamination given the current geochemical conditions. These same processes also may act upon chlorinated solvents within the immediate source area, both as electron donors and electron acceptors.

6.2.3.3 Potential Receptor Exposure Pathways

A pathway analysis identifies the potential human and ecological receptors that could come into contact with site-related contamination and the pathways through which these receptors might be exposed. To have a completed exposure pathway, there must be a source of contamination, a mechanism(s) of release, a pathway of transport to an exposure point, an exposure point, and a receptor. If any of these elements do not exist, the exposure pathway is considered incomplete, and receptors will not come into contact with site-related contamination. Evaluation of the potential long-term effectiveness of any remedial technology or remedial alternative as part of this demonstration project includes determining the potential for pathway completion. If a completed exposure pathway exists, potential long-term remedial options may still be sufficient to maintain exposure concentrations below regulatory action levels. Establishing site-specific, risk-based cleanup levels is beyond the scope of this TS.

Assumptions about current and future land uses at a site form the basis for identifying potential receptors, potential exposure pathways, reasonable exposure scenarios, and appropriate remediation goals. USEPA (1991) advises that the land use associated with the highest (most conservative) potential level of exposure and risk that can reasonably be expected to occur should be used to guide the identification of potential exposure pathways and to determine the level to which a site must be remediated.

Groundwater beneath LF-03 flows generally to the east-northeast toward an area of open grassland and Crow Creek, and also toward the Nob Hill Subdivision. Because the site is near residential facilities (Carlin Heights and Nob Hill Subdivisions), on-base and off-base residents and workers are the most probable potential receptors that could be exposed to any site-related contamination.

6.2.3.4 Remediation Goals for Groundwater

USEPA MCLs (1996) for chlorinated ethenes are presented in Table 6.1. Compounds detected in LF-03 groundwater that exceed these standards are TCE and *cis*-1,2-DCE. VC has historically been detected at concentrations exceeding its MCL (Table 4.1), but was not detected in 1999. For this TS, the primary remedial objective for evaluation of remediation technologies for shallow groundwater is to reduce contaminant concentrations in groundwater to below federal regulatory criteria at a downgradient point of compliance. To accomplish this, remedial alternatives focus on limiting migration of dissolved contaminant concentrations exceeding MCLs away from Site LF-03. It is unlikely that groundwater from Site LF-03 would be ingested by humans, because there are no current downgradient water supplies in close proximity to the site. However, the MCL of 5 µg/L for TCE will be used to evaluate the effectiveness, implementability, and cost of remedial alternatives in this TS.

TABLE 6.1
GROUNDWATER QUALITY STANDARDS
LF-03 RNA TS
F.E. WARREN AFB, WYOMING

Compound	USEPA MCL[a/] (µg/L)
Tetrachloroethene	5
Trichloroethene	5
1,1-Dichloroethene	7
Cis-1,2-Dichloroethene	70
Vinyl Chloride	2

[a/] USEPA MCL = US Environmental Protection Agency (1996) Maximum Contaminant Level.

Available data suggest there are no completed exposure pathways involving human and ecological receptors exposed to contaminated groundwater under current conditions. Site LF-03 is part of a secured military base, so institutional controls can be incorporated to limit any future intrusive activity at the site. The required period of any groundwater and soil institutional controls associated with the selected remedial alternative is likely to expire before any anticipated future land use changes. Off-base migration of dissolved contaminants in concentrations exceeding MCLs appears unlikely, given the groundwater flow direction and discharge to Crow Creek at the eastern base boundary.

6.2.4 Summary of Remedial Option Screening

Several remedial options have been identified and screened for use in treating shallow groundwater at the site. Table 6.2 identifies the initial remedial technologies and approaches considered as part of this demonstration and those retained for detailed comparative analysis. Screening was conducted systematically by considering the program objectives of the AFCEE natural attenuation demonstration, physiochemical properties of groundwater contaminants detected at LF-03, and other site-specific characteristics such as hydrogeology, geochemistry, land use assumptions, potential receptor exposure pathways, and appropriate remediation goals. All of these factors will influence the technical effectiveness, implementation, and relative cost of technologies for remediating shallow groundwater underlying and migrating from the site. The remedial options retained for development of remedial alternatives and comparative analysis include institutional controls, natural attenuation, LTM, source characterization, and source removal (excavation). In addition, the emerging technologies of iron filings trenches and injection of an agent (carbon source) to induce reducing conditions for reductive dehalogenation were retained for future consideration in the event that selected remedial options are deemed insufficient.

6.3 BRIEF DESCRIPTION OF REMEDIAL ALTERNATIVES

This section describes how remedial technologies retained from the screening process were combined into three remedial alternatives for the study area. Sufficient information on each remedial alternative is provided to facilitate a comparative analysis of effectiveness, implementability, and cost in Section 6.4. While the technologies of interceptor trenches and injection of a carbon source were not considered as alternatives, a brief discussion of these potential approaches is included for the readers information.

6.3.1 Alternative 1 - MNA and Institutional Controls with Long-Term Groundwater Monitoring

MNA is achieved when natural attenuation mechanisms bring about a reduction in the total mass or concentration of a contaminant in the soil or dissolved in groundwater. MNA results from the integration of several subsurface attenuation mechanisms that are classified as either destructive or nondestructive. Destructive attenuation mechanisms include biodegradation, abiotic oxidation, and hydrolysis. Nondestructive attenuation mechanisms include sorption, dilution (caused by dispersion and infiltration), and volatilization. In some cases, MNA will reduce dissolved contaminant concentrations below numerical concentration goals intended to be protective of human health and the environment. As indicated by the evidence of natural attenuation described in Section 4, these processes likely have occurred in the immediate LF-03 source area, and may continue to reduce contaminant mass.

Implementation of Alternative 1 would require the use of institutional controls such as land use restrictions, and LTM. Land use restrictions may include placing long-term restrictions on groundwater well installations within and downgradient from the plume area. The intent of these restrictions would be to reduce potential receptor exposure to

TABLE 6.2
INITIAL TECHNICAL IMPLEMENTABILITY SCREENING OF TECHNOLOGIES AND PROCESS OPTIONS FOR GROUNDWATER REMEDIATION
LF-03 RNA TS
F.E. WARREN AFB, WYOMING

General Response Action	Technology Type	Process Option	Implementability	Effectiveness	Relative Cost	Retain
Long-Term Monitoring	Periodic Groundwater Monitoring	Confirmation Wells	Many monitoring wells are available to confirm the progress of remediation. Sufficient space exists for additional wells.	Necessary for all remedia-tion strategies	Low	Yes
		Sentry Wells	Sufficient distance exists between the plume and point-of-compliance to locate several wells.	Necessary	Low	Yes
Institutional Controls	Groundwater Use Control	Land Use Control/Regulate Well Permits	The plume lies within the Base boundary, and land and groundwater use are under Base jurisdiction.	Necessary	Low	Yes
		Seal/Abandon Existing Wells	No production wells are known to exist in the current or predicted plume area.	Not required at this site	Low	No
		Point-of-Use Treatment	No shallow groundwater is extracted from the plume area for any use.	Not required at this site	Moderate	No
	Public Education	Meetings/ Newsletters	Base public relations and environmental management offices have many information avenues through which to communicate to workers and residents.	Necessary	Low	Yes
Containment of Plume	Hydraulic Controls	Interceptor Trench Collection	Limited effectiveness and high cost due to depth of groundwater, depth to aquitard, and size of plume. Physical controls not required at this site.	Low	High	No
		Groundwater Extraction	Future migration of dissolved plume is projected to be minimal. Does not comply with program objectives.	Moderate	Moderate	No
	Physical Controls	Slurry Walls/Grout Curtains	Limited effectiveness and high cost due to depth of groundwater, depth to aquitard, and size of plume. Physical controls not required at this site.	Low	High	No
		Sheet Piling	Limited effectiveness and high cost due to depth of groundwater, depth to aquitard, and size of plume. Physical controls not required at this site.	Low	High	No
	Reactive/ Semi-Permeable Barriers	Biologically Active Zones/ Iron Filings Trench	Degradation of CAHS may be stimulated by allowing groundwater to flow through a nutrient-rich zone or zero-valent zone. New, emerging technologies	Moderate	High	Yes

TABLE 6.2 (continued)
INITIAL TECHNICAL IMPLEMENTABILITY SCREENING OF
TECHNOLOGIES AND PROCESS OPTIONS FOR GROUNDWATER REMEDIATION
LF-03 RNA TS
F.E. WARREN AFB, WYOMING

General Response Action	Technology Type	Process Option	Implementability	Effectiveness	Relative Cost	Retain
In Situ Groundwater Treatment	Biological	Oxygen Enhanced Biodegradation (Biosparging)	Oxygen is injected within and/or downgradient of plume to limit plume migration by enhancing biodegradation and reducing contaminant concentrations. TCE is not aerobically biodegradable.	Low	Low	No
		Nutrient Enhanced Biodegradation (Injection)	Nutrients are injected within and/or downgradient of plume to limit plume migration by enhancing biodegradation of CAHs by reductive dehalogenation. Will enhance anaerobic degradation of CAHs by inducing reducing conditions. Not proven to be more effective than natural attenuation, an emerging technology	Moderate	Moderate	Yes
	Chemical/ Physical	Natural Attenuation	A combination of natural biological, chemical, and physical removal mechanisms which occur to varying degrees on every site. Groundwater sampling at LF-03 indicates that this is an ongoing remediation process.	High	Low	Yes
		Air Sparging (Volatilization)	Injection of air into contaminated aquifer creating a mass transfer of CAHs, specifically TCE, into air bubbles and vadose zone. Similar to biosparging in effectiveness; however, more mass is transferred rather than destroyed. Most effectively used downgradient of the source so as not to upset anaerobic conditions promoting reductive dechlorination in the source area.	Low	Low	No
Source Removal/ Groundwater Remediation	Groundwater Extraction	Vertical Pumping Wells	Source area of groundwater plume is pumped by installing submersible pumps in source area wells. Limited by contaminant mass transfer rates into the groundwater.	Moderate	Moderate	No
Aboveground Groundwater Treatment	Biological	Bioreactors	High flow rates require excessive retention times and large reactors. CAHs are often volatilized in these systems.	Moderate	High	No
	Chemical/ Physical	Air Stripping	Cost-effective technology for removing CAHs from groundwater at high flow rates. Potential permitting for air emissions.	High	Moderate	No
		Activated Carbon	Cost prohibitive for more concentrated CAHs. Creates a carbon disposal problem.	Moderate	High (O&M)	No
		Direct Discharge to Industrial Waste Water Treatment Plant	Implementable option only when an Industrial Waste Water Treatment Plant (IWWTP) is readily available and capable of handling CAHs and hydraulic loading. IWWTP not available for this site.	High	Low	No
		UV/Ozone Reactors	High flow rates require lengthy retention times and large, costly reactors.	Moderate	High	No

TABLE 6.2 (Continued)
INITIAL TECHNICAL IMPLEMENTABILITY SCREENING OF TECHNOLOGIES AND PROCESS OPTIONS FOR GROUNDWATER REMEDIATION
LF-03 RNA TS
F.E. WARREN AFB, WYOMING

General Response Action	Technology Type	Process Option	Implementability	Effectiveness	Relative Cost	Retain
Treated Groundwater Disposal	Discharge to IWWTP	IWWTP	Implementable option only when an IWWTP is available and capable of handling hydraulic loading. IWWTP is not available.	High	Low	No
	Discharge to Sanitary Sewer	Sanitary Sewer	Implementable option only when access to a sanitary sewer exists and hydraulic loading is acceptable.	High	Low	No
	Treated Groundwater Reinjection	Vertical Injection Wells	Injection wells subject to clogging, high maintenance, and permitting.	Moderate	Moderate	No
		Injection Trenches	Requires large trenches and can be subject to injection well permitting.	Moderate	Moderate	No
	Discharge to Surface Waters	Storm Drains or Surface Ditch	Generally requires NPDES or other discharge permit.	High	Low	No
Source Removal/Soil Remediation	Excavation/ Treatment	Landfilling	Some excavation may economically be feasible if it can be shown that source area is generally less than 4,000 cubic yards.	Moderate to High	Moderate	Yes
		Biological Landfarming	Some excavation may be feasible at this site. For reasons of risk and cost reduction, *in-situ* methods or landfilling preferable when possible.	Moderate to High	Moderate	No
		Thermal Desorption	Some excavation may be feasible at this site. For reasons of risk and cost reduction, *in-situ* methods or landfilling preferable when possible.	Moderate to High	High	No
	In Situ	Bioventing	Air injection/extraction to increase soil oxygen levels and stimulate biodegradation of fuel residuals. Conductivity of site soils to air movement would be greater than to water movement. Might stimulate cometabolism of CAHs during the biodegradation of fuel contamination.	Moderate to High	Low	No
		Soil Vapor Extraction	Air extraction to increase soil oxygen levels and extract VOCs from vadose zone. Conductivity of site soils to air movement would be greater than to water movement. May be subject to air emissions permitting.	High	Low to Moderate	No

TABLE 6.2 (Concluded)
INITIAL TECHNICAL IMPLEMENTABILITY SCREENING OF TECHNOLOGIES AND PROCESS OPTIONS FOR GROUNDWATER REMEDIATION
LF-03 RNA TS
F.E. WARREN AFB, WYOMING

General Response Action	Technology Type	Process Option	Implementability	Effectiveness	Relative Cost	Retain
Source Removal/Soil Remediation (continued)	*In-Situ* (continued)	Soil Washing	Water and/or surfactant solution are forced through zones of residual contamination to enhance contaminant partitioning into the groundwater. Most effective in homogeneous sandy soils.	Low	High	No
	Mobile NAPL Recovery	Dual-Pump Systems	NAPL has not been detected at the site.	Moderate	High	No
		Skimmer Pumps, Bailers, Wicks	NAPL has not been detected at the site.	Moderate	Low to Moderate	No
		Total Fluids Pumping	NAPL has not been detected at the site.	Moderate	High	No
		Vacuum-enhanced extraction	NAPL has not been detected at the site.	Moderate to High	Moderate to High	No

contaminants by legally restricting activities within areas affected by site-related contamination.

Long-term monitoring would be performed at a regular frequency and would consist of sampling a set of wells, including upgradient, source area, plume extent, and surface water sampling points along Crow Creek (Section 7). For this site, it is assumed that 30 years of monitoring (consisting of annual monitoring for 4 years followed by biennial monitoring for 26 years) would be needed to establish plume behavior (i.e., expanding, stable, or shrinking) and that contaminant concentrations are decreasing. The recommended site-specific LTM strategy is provided in Section 7. On the basis of predictive contaminant fate and transport model results (Section 6.4), it is unlikely that contaminant concentrations exceeding groundwater MCLs would approach a potential receptor exposure point. Nevertheless, LTM is the technical mechanism used to evaluate the progress of natural attenuation processes and to ensure that remedial objectives are being met. Detection of TCE or *cis*-1,2-DCE in excess of their individual MCLs at a sentry well or surface water sampling point may require additional evaluation to assess contaminant migration, to determine the probable extent of migration, and to determine if additional corrective action is necessary. In either case, land use restrictions would require reevaluation.

Public education on the selected alternative would be developed to inform Base personnel and residents of the scientific principles underlying source reduction and MNA. This education could be accomplished through public meetings, presentations, press releases, and posting of signs where appropriate. Periodic site reviews could also be conducted annually using data collected from the LTM program. The purpose of these periodic reviews would be to evaluate the extent of contamination, assess contaminant migration and attenuation through time, document the effectiveness of source removal and/or institutional controls at the site, and reevaluate the need for additional remedial actions at the site.

6.3.2 Alternative 2 – Source Characterization and Removal, MNA, and Institutional Controls with Long-Term Groundwater Monitoring

Additional source characterization activities are recommended for site LF-03 to reduce the source mass for TCE. Alternative 2 therefore includes additional source characterization by a soil gas survey, followed by source removal (excavation) and LTM. As with Alternative 1, institutional controls and LTM would be required. LTM wells would be the same as described for Alternative 1, and it is assumed that 30 years of monitoring would be needed to establish whether the plume is stable or shrinking and that contaminant concentrations are decreasing.

6.3.3 Alternative 3 – Source Characterization and Total Source Removal, MNA, and Institutional Controls with Long-Term Groundwater Monitoring

Alternative 3 includes additional source characterization by a soil gas survey, followed by removal of the total source area, and LTM. As with Alternatives 1 and 2, institutional controls and LTM would be required. LTM wells would be the same as described for Alternative 1, and it is assumed that 30 years of monitoring would be needed to establish

whether the plume is stable or shrinking and that contaminant concentrations are decreasing.

6.3.4 Alternate Technologies

Reductive dehalogenation is a known mechanism for the biodegradation of many chlorinated solvents. Only mildly reducing conditions in the source area were documented for LF-03. Several approaches for stimulating this process have been demonstrated (injection of lactate for example), although no commercially viable and widely accepted process for *in situ* bioremediation of chlorinated solvents has emerged.

The most common approach utilized to date has been addition of a carbon source dissolved in groundwater. This approach may prove cost effective in some applications but in many cases may have difficulty competing with pump and treat because the carbon source must be continuously injected. Other approaches involving the placement of solid materials that release carbon are promising, but the cost of carbon placement will be high. AFCEE is currently investigating the use of vegetable oil as a carbon source that can be injected in a single one-time application by conventional means. Due to the slow dissolution to groundwater of the vegetable oil, it is thought this would provide an adequate carbon source for the lifetime of the remediation treatment.

Due to the unproven nature of this technology, carbon source injection was not selected in any alternative. However, this technology could be reevaluated in the future when more data regarding the effectiveness, time-frame for remediation, lifetime, and long-term cost of this technology are available.

Plume capture downgradient from the source area and prior to discharge to Crow Creek also could be accomplished by installing an iron filings trench (permeable reaction wall). With an iron filings trench, groundwater contaminated with CAHs flows through granular, zero-valent iron in a trench, which is excavated perpendicular to the axis of groundwater flow. Dissolved CAHs are degraded through a series of less-chlorinated intermediates to non-toxic, non-chlorinated end products. However, iron filings trenches are a new, relatively unproven technology.

The cost for the iron filings backfill can range from $400 to $450 per ton (Focht *et al.*, 1996) (approximately $740 to $840 per cubic yard), and the effective lifetime of an iron filings trench is not known. There is a potential for precipitation of dissolved minerals within the trench due to pH changes across the trench boundary, resulting in clogging. Therefore, an iron filings trench may require periodic rehabilitation or replacement. Given this potential maintenance, it would be desirable to shorten the trench length to the degree possible using "funnel walls" constructed using sheet piling, slurry walls, or grout curtains to direct water into the iron filings trench. This is often referred to as the funnel-and-gate method. This in turn reduces long-term operation and maintenance (O&M) costs.

Due to the unproven nature of this technology, the potential for high long-term maintenance costs, and the potential for surface discharge of groundwater, an iron filings trench was not selected in any alternative. However, installation of a permeable reaction

wall could be reevaluated in the future when more data regarding the effective lifetime and long-term cost of this technology are available.

6.4 EVALUATION OF ALTERNATIVES

This section provides a comparative analysis of each of the remedial alternatives based on the effectiveness, implementability, and cost criteria. A summary of this evaluation is presented in Section 6.5.

6.4.1 Alternative 1 - RNA and Institutional Controls with Long-Term Groundwater Monitoring

6.4.1.1 Effectiveness

Alternative 1 is based on the effectiveness of natural processes that minimize contaminant migration and reduce contaminant mass or concentrations over time as well as the effectiveness of institutional controls. To evaluate Alternative 1, the MODFLOW and MT3D96 numerical contaminant transport model presented in Section 5 was used to predict the future extent of TCE groundwater contamination. The Alternative 1 simulation assumes the TCE source from the calibrated model continues to contribute TCE to groundwater for another 50 years (total simulation time of 89 years from initial source release). The TCE source is modeled with a source weathering rate of 7.3 percent per year, due to processes such as volatilization, dissolution, and biodegradation (Section 5.4.4.1). Thus, the model assumes that after 1999, the source loading rates decreased geometrically by 7.3 percent per year (each year's source strength was decreased by 7.3 percent from the previous year's strength).

The predicted extent of TCE for Alternative 1 after 10, 20, and 30 years (the years 2009, 2019, and 2029, respectively) are shown on Figure 6.1. A 29-year period was assumed for the TCE plume calibration in Section 5, and a 50-year time period was used to predict plume behavior in the future. The extent of the TCE plume after a 50 year simulation was negligible (concentrations less than 5 µg/L). A 30 year time period was therefore deemed sufficient to evaluate the lifetime of the simulated TCE plume. The predicted extent of TCE contamination after 30 years is also used as the basis for the long-term monitoring network LTM well locations discussed in Section 7.

The model predicts maximum TCE concentrations of up to 50 µg/L in shallow groundwater in the vicinity of wells 209 and PES-1S after 10 years, and it predicts the plume will extend to Crow Creek based on the 1 µg/L isopleth. After 30 years, TCE concentrations continue to decline to approximately 10 µg/L, with the center of mass of the TCE plume located downgradient between wells PES-6S and 203. In no circumstance does the 5 µg/L isopleth discharge to Crow Creek. The apparent expansion of the simulated TCE plume primarily involves low concentrations of TCE (less than 10 µg/L), which is subject to some uncertainty based on numerical dispersion in the model.

TCE concentrations should not exceed MCLs at the furthest downgradient monitoring wells (Figure 6.1). Speculative model predictions after 10 years indicate that the TCE plume may migrate approximately 500 feet northeast to Crow Creek. Groundwater

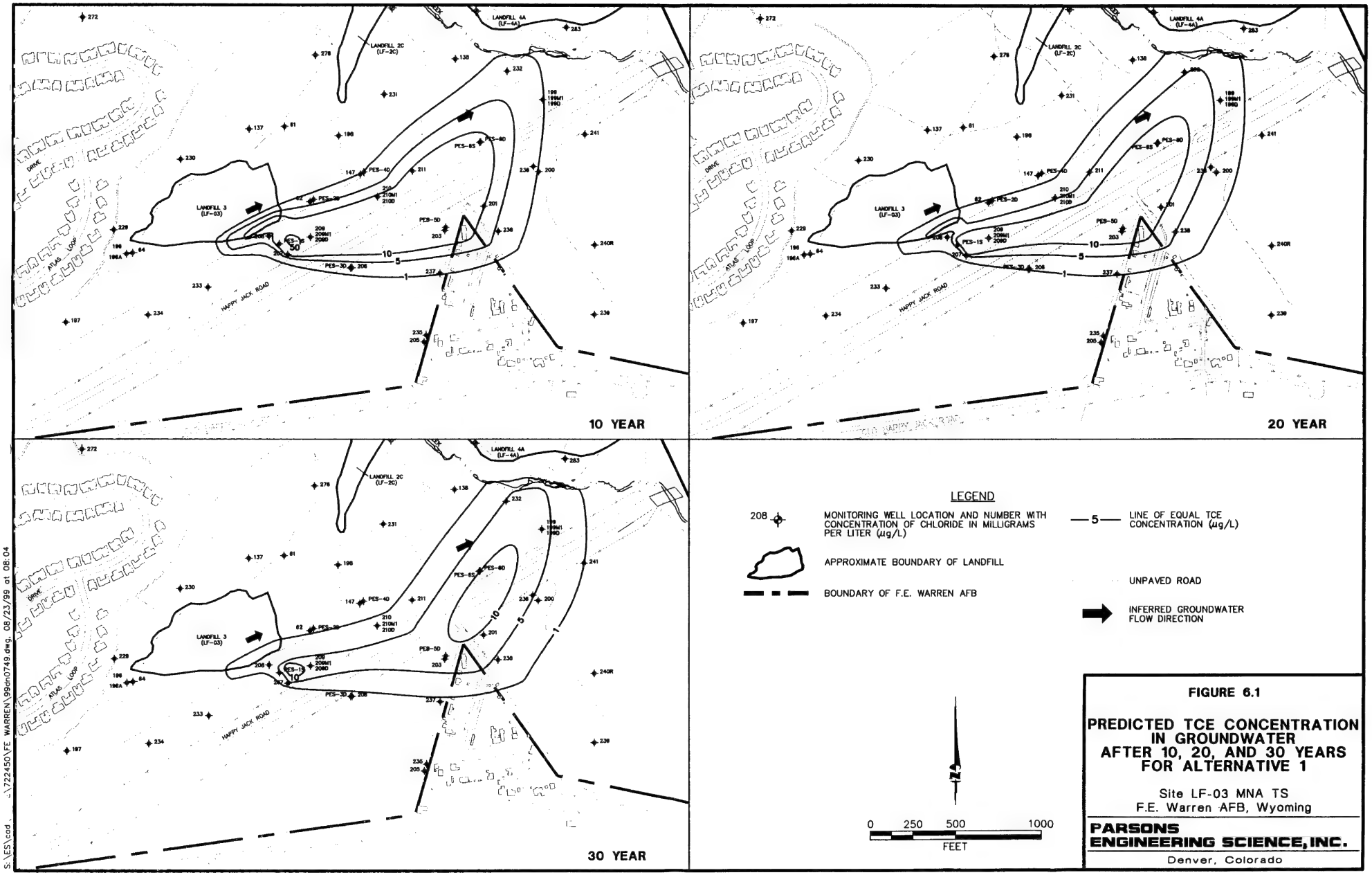

FIGURE 6.1

PREDICTED TCE CONCENTRATION IN GROUNDWATER AFTER 10, 20, AND 30 YEARS FOR ALTERNATIVE 1

Site LF-03 MNA TS
F.E. Warren AFB, Wyoming

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monitoring at the LTM wells will allow for continued evaluation of contaminant migration and ensure the safety of this alternative. While this alternative would not cease to be protective if the contaminant concentrations exceeding MCLs were detected in downgradient LTM wells, such an instance would indicate that site conditions should be reevaluated.

The effectiveness of this remedial alternative requires that only properly protected site workers conduct future intrusive site activities or construction activities within the plume area. Reasonable land use assumptions for the plume area indicate that exposure is unlikely unless excavation or drilling activities bring groundwater or saturated soil to the surface. Long-term land use restrictions would be required to ensure that shallow groundwater is not pumped or removed for potable use within about 1,000 feet from the margins of the existing contaminant plume. Existing health and safety plans should be enforced to reduce worker exposures during additional excavation or installing and monitoring additional wells.

Compliance with program goals is one component of the long-term effectiveness evaluation criterion. Alternative 1 would satisfy program objectives designed to promote RNA as a component of site remediation and to scientifically document natural processes. In addition, the alternative satisfies waste minimization goals and the program goal for cost effectiveness.

Apart from the administrative concerns associated with the enforcement of long-term land use restrictions and long-term groundwater monitoring programs, this remedial alternative should provide reliable, continued protection. It is assumed that dissolved contaminant concentrations will exceed state and federal criteria throughout the plume for approximately 30 years under Alternative 1. Furthermore, it is assumed that sampling will be performed every year for 4 years, and biennially for the remaining 26 years, to demonstrate that MNA is reducing dissolved contaminant concentrations and limiting plume migration.

6.4.1.2 Implementability

Alternative 1 is not technically difficult to implement. Long-term management efforts would be required to ensure proper sampling procedures are followed. Periodic site reviews should be conducted to confirm the adequacy and completeness of LTM data and verify the effectiveness of this remediation approach. There also may be administrative concerns associated with long-term enforcement of groundwater use restrictions. Leaving contaminated soil and groundwater in place may impact future land use within the source area. However, with the exception of any subsurface work at the site, the risk for Base personnel of exposure to contaminants will be limited. If required, the public and the regulators would have to be informed of the benefits and limitations of the MNA option. Educational programs are not difficult to implement. Where the effectiveness of this option has been supported, the initial regulatory reaction to this alternative has been positive.

6.4.1.3 Cost

The cost of Alternative 1 is summarized in Table 6.3, and cost calculations are included in Appendix D. No capital costs are necessary. Included in the $1,609,000 total cost estimate for Alternative 1 are the costs of maintaining institutional controls and long-term monitoring at 31 LTM groundwater wells and 2 surface water stations for a total of 30 years. If the dissolved contaminant concentrations at the site decrease rapidly or drop below MCLs for consecutive sampling events, then monitoring may be reduced or eliminated. Conversely, significant increases for consecutive sampling events or a significant increase in plume extent could warrant an increase in sampling frequency or implementation of another remedial alternative.

TABLE 6.3
ALTERNATIVE 1 - COST ESTIMATE
SITE LF-03 RNA TS
F.E. WARREN AFB, WYOMING

Monitoring Costs	Total Cost [a/]
Conduct Annual Monitoring of 31 Groundwater Wells and 2 Surface Water Stations (2000 to 2004)	$194,400
Conduct Biennial Monitoring of 31 Groundwater Wells and 2 Surface Water Stations (2005 to 2029)	$974,700
Site Management (Maintain Institutional Controls/Public Education) and Reporting (30 years)	$440,300
Total Cost of Alternative 1	**$1,609,000**

[a/] Based on an annual inflation rate of 4 percent.

6.4.2 Alternative 2 – Source Characterization and Removal, MNA, and Institutional Controls with Long-Term Groundwater Monitoring

6.4.2.1 Effectiveness

Alternative 2 includes additional source characterization (soil gas survey), followed by source removal (excavation) and LTM. Alternative 2 is based on locating and removing the source of TCE contamination as well as natural processes that minimize contaminant migration and reduce contaminant mass over time. To evaluate Alternative 2, the MODFLOW and MT3D96 numerical contaminant transport model presented in Section 5 was used to predict the future extent of TCE groundwater contamination after source

removal. The Alternative 2 simulation assumes the TCE source from the calibrated model is reduced by 50 percent for 2 years, then is reduced by 7.3 percent per year as in Alternative 1.

The predicted extent of TCE for Alternative 2 after 10, 20, and 30 years (the years 2009, 2019, and 2029, respectively) are shown on Figure 6.2. As with Alternative 1, the extent of the TCE plume after a 50 year simulation was negligible. The model predicts maximum TCE concentrations of less than 50 µg/L in shallow groundwater in the vicinity of wells 209 and PES-1S after 10 years, due to source reduction. Outside of the source area, the plume extends to Crow Creek in 10 years. Similar to Alternative 1, downgradient TCE concentrations continue to decline to approximately 10 µg/L in 30 years, with the center of mass of the TCE plume located downgradient between wells PES-6S and 203.

Because a significant mass of TCE has already migrated downgradient from the source area, source reduction has little effect on the downgradient migration and persistence of the TCE plume. The primary benefit of source reduction is to lower TCE concentrations within the core of the plume.

Further delineation of TCE sources and hot spots at LF-03 can be accomplished by implementing a soil gas survey in and near the landfill. For costing purposes, Alternative 2 includes a soil gas survey on a grid spacing of 20 feet (Appendix D). Results of the soil gas survey can be used to identify elevated concentrations of TCE in soil and shallow groundwater. Source removal by excavation can then be conducted based on results of the soil gas survey.

Alternative 2 should provide reliable, continuous protection. This alternative complies with AFCEE program goals, because MNA remains the predominant remediation method for contaminants dissolved in groundwater at the site. This remedial alternative, however, will result in the generation of additional contaminated soil that may require treatment and/or disposal. The effectiveness of MNA and institutional controls with LTM is as discussed for Alternative 1 in Section 6.4.1.1.

6.4.2.2 Implementability

Alternative 2 is not technically difficult to implement. Recommended site characterization activities are standard procedures. The technical and administrative implementability concerns associated with the natural attenuation and LTM components of this remedial alternative are similar to those discussed for Alternative 1.

6.4.2.3 Cost

The estimated capital and operating costs of Alternative 2 are shown in Table 6.4. The total cost of Alternative 2 is $1,891,000 (Appendix D). The cost of Alternative 2 is increased from the costs of Alternative 1 by the addition of the soil gas survey and source excavation. LTM is assumed to occur every year for 4 years, and biennially for an additional 26 years, to ensure that natural attenuation is reducing contaminant

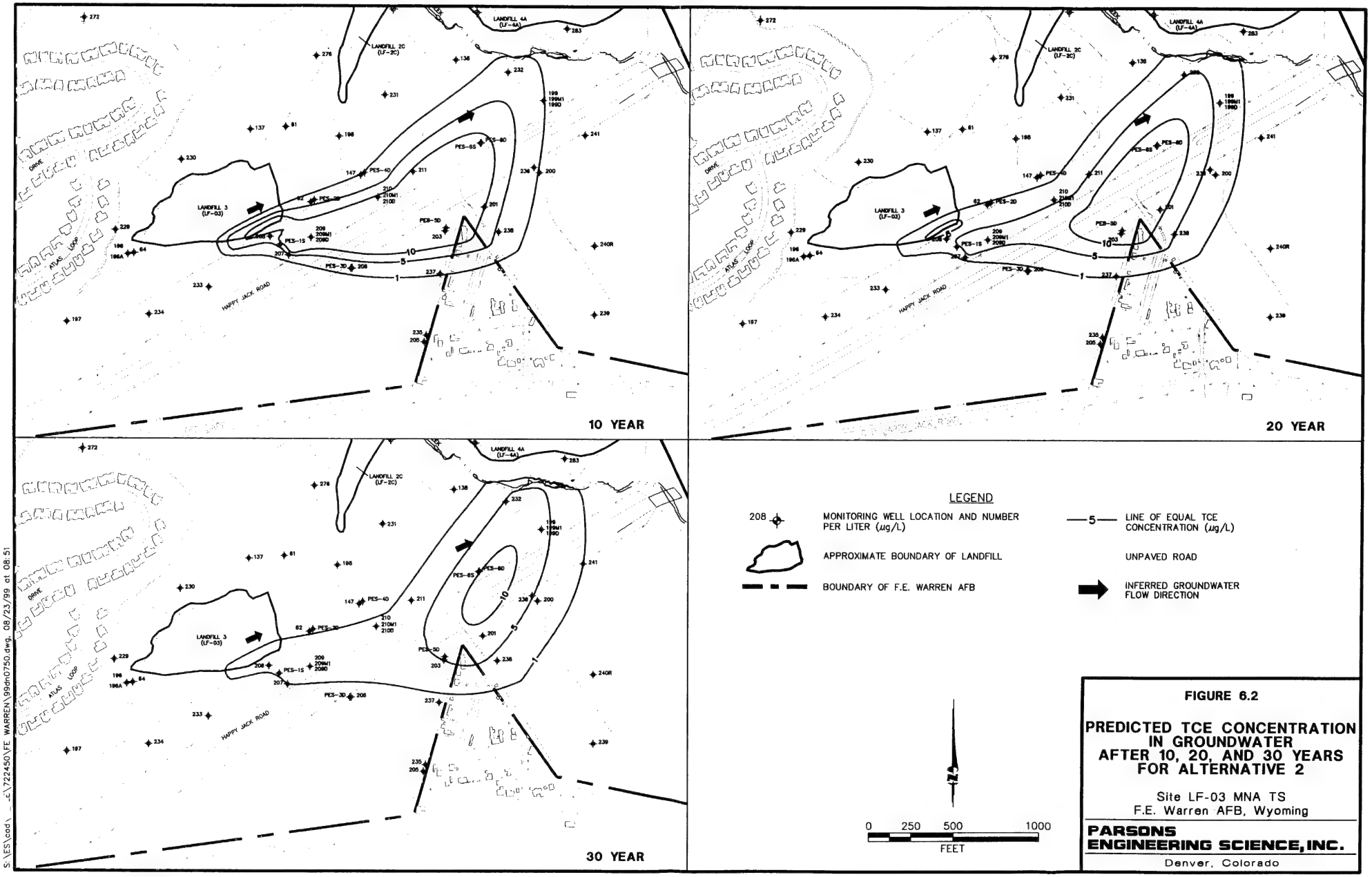

FIGURE 6.2

PREDICTED TCE CONCENTRATION IN GROUNDWATER AFTER 10, 20, AND 30 YEARS FOR ALTERNATIVE 2

Site LF-03 MNA TS
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concentrations. The capital expense and annual costs for LTM and institutional controls are assumed to be the same as for Alternative 1.

TABLE 6.4
ALTERNATIVE 2 - COST ESTIMATE
SITE LF-03 RNA TS
F.E. WARREN AFB, WYOMING

Capital Costs	Total Cost [a/]
Perform Soil Gas Survey for Source Characterization	$79,100
Soil Excavation and Disposal	$202,800
Total Cost of Alternative 1	**$1,609,000**
Subtotal for Cost of Alternative 2	**$281,900**
Total Cost of Alternative 2	**$1,891,000**

[a/] Based on an annual inflation factor of 4 percent.

Soil gas survey costs assume a 20-foot node-centered grid for an area of 25,600 ft^2, a total of 240 sampling points. The area for the soil gas survey was assumed to be limited to the southern portions of the landfill and "hotspots" identified by groundwater sampling. Excavation was assumed to cover a total area of 15,000 ft^2 to a depth of 15 feet (approximate depth to groundwater). Actual excavation quantities are dependent on results of the soil gas survey, and could vary substantially. Therefore, costs for Alternative 2 are for comparison purposes only.

6.4.3 Alternative 3 – Source Characterization and Total Source Removal, MNA, and Institutional Control with Long-Term Monitoring

6.4.3.1 Effectiveness

Alternative 3 is identical to Alternative 2 with the exception of total source removal. Alternative 3 is based on locating and removing the entire source of TCE contamination, as well as natural processes that minimize contaminant migration and reduce contaminant mass over time. To evaluate Alternative 3, the MODFLOW and MT3D96 numerical contaminant transport model presented in Section 5 was used to predict the future extent of TCE groundwater contamination after total source removal. The Alternative 3 simulation was run with all source terms removed as of 1999 to model a total source removal scenario.

The predicted extent of TCE for Alternative 3 after 10, 20, and 30 years (the years 2009, 2019, and 2029, respectively) are shown on Figure 6.3. As with Alternatives 1 and 2, the extent of the TCE plume after a 50 year simulation was negligible. The model predicts maximum TCE concentrations of less than 10 ug/l in shallow groundwater in the

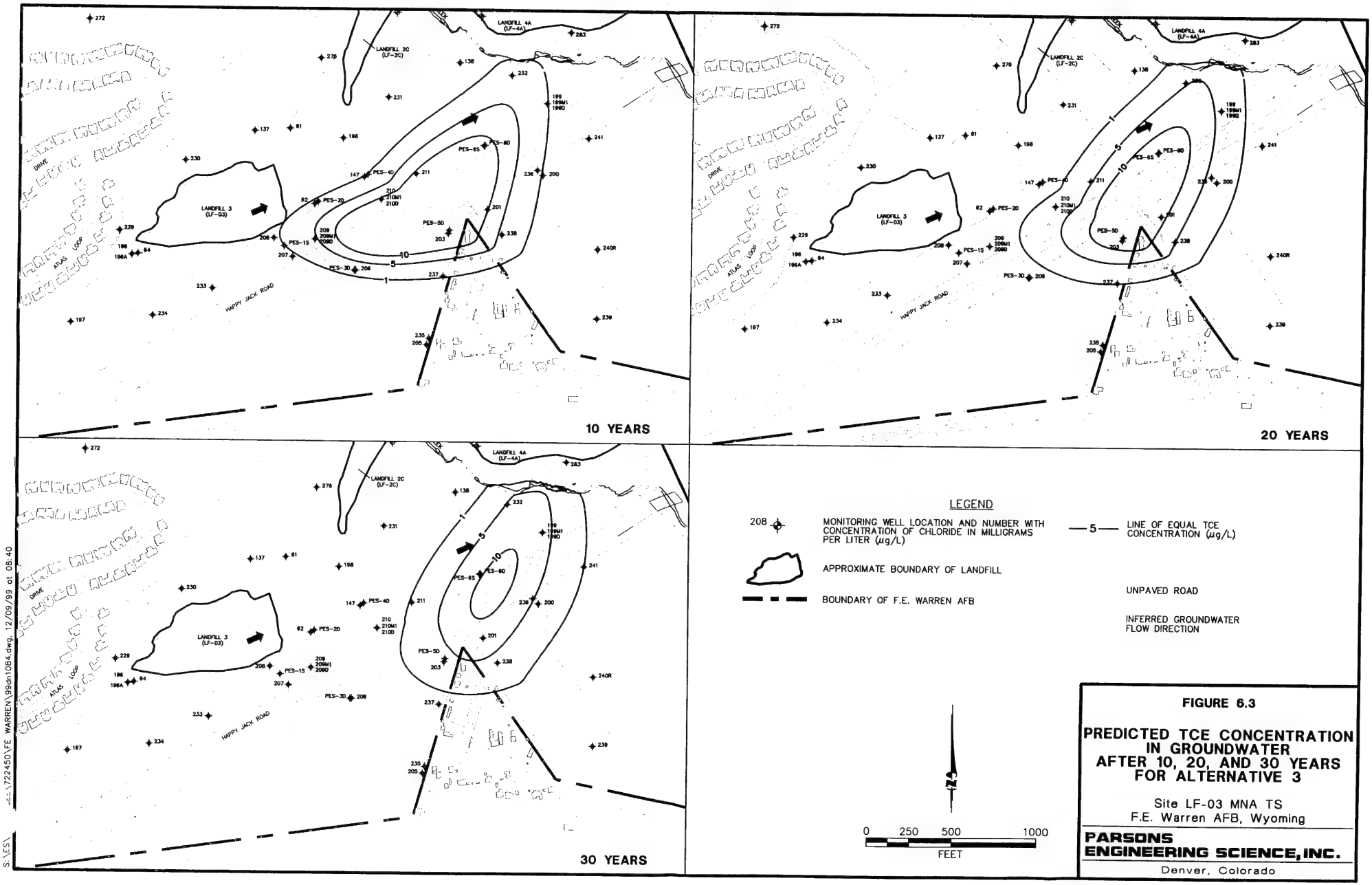

FIGURE 6.3

PREDICTED TCE CONCENTRATION IN GROUNDWATER AFTER 10, 20, AND 30 YEARS FOR ALTERNATIVE 3

Site LF-03 MNA TS
F.E. Warren AFB, Wyoming

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vicinity of wells 209 and PES-1S after 10 years, due to source removal. Outside of the source area, the plume still extends to Crow Creek in 10 years as predicted by the Alternative 2 simulation. Downgradient TCE concentrations also continue to decline to approximately 10 ug/l in 30 years, similar to the Alternative 1 and 2 predictions, with the center of mass of the TCE plume located downgradient between well PES-6S and 203.

Because a significant mass of TCE has already migrated downgradient from the source area, source removal has little effect on the downgradient migration and persistence of the TCE plume. The primary benefit of total source removal is to eliminate uncertainty and any future risk associated with a lack of characterization of the TCE source. A secondary benefit is to reduce TCE concentrations and persistence immediately downgradient of the plume source area.

Alternative 3 should provide reliable, continuous protection. This alternative also complies with AFCEE program goals, because, as with Alternative 2, MNA remains the predominant remediation method for contaminants dissolved in groundwater at the site. This remedial alternative also may result in the generation of additional contaminated soil that may require treatment and/or disposal. The effectiveness of MNA and institutional controls with LTM is as discussed for Alternative 1 in Section 6.4.1.1.

6.4.3.2 Implementability

As with Alternative 2, Alternative 3 is not technically difficult to implement. Recommended site characterization activities are standard procedures. The technical and administrative implementability concerns associated with the natural attenuation and LTM components of this remedial alternative are similar to those discussed for Alternative 1.

6.4.3.3 Cost

The estimated capital and operating costs of Alternative 3 are identical to those of Alternative 2 with the exception of the estimate for soil excavation and disposal. This cost will depend on the volume of soil to be removed.

6.5 RECOMMENDED REMEDIAL APPROACH

Three remedial alternatives have been evaluated for remediation of groundwater at LF-03. Components of the alternatives evaluated include MNA with LTM of groundwater, institutional controls, source characterization, and partial or total source removal. Table 6.5 summarizes the results of the evaluation based upon effectiveness, implementability, and cost criteria. Due to the lack of adequate source characterization, AFCEE recommends Alternatives 2 and 3 as balanced and cost-effective options for risk reduction at the study area. The Base may want to consider alternative remedial options if the time frame to remediation is not acceptable.

Each alternative makes use of natural attenuation mechanisms to reduce plume migration and toxicity. Implementation of Alternatives 2 and 3 may not substantially decrease the time frame for remediation, but confidence in model predictions is limited based the lack of source characterization.

TABLE 6.5
SUMMARY OF REMEDIAL ALTERNATIVES EVALUATION
LF-03 RNA TS
F.E. WARREN AFB, WYOMING

Remedial Alternative	Effectiveness	Implementability	Present Worth Cost Estimate
Alternative 1 - Natural Attenuation - Long-Term Monitoring - Institutional Controls	Contaminant mass, volume, and toxicity will be slowly reduced over time, but the dissolved plume may persist for over 30 years, necessitating a potentially lengthy period of LTM and institutional controls.	Readily implementable. Groundwater water quality monitoring required for an estimated minimum of 30 years, and potentially longer. Institutional controls, including land and groundwater use controls, may be required for approximately 30 years due to the persistance of elevated dissolved TCE concentrations. Minimal exposure to potential receptors if institutional controls are implemented. If significant plume migration occurs and completion of exposure pathways is possible, then additional remedial work may be required.	**$1,609,000**
Alternative 2 - Source Characterization - Source Reduction - Natural Attenuation - Long-Term Monitoring - Institutional Controls	Similar to Alternative 1, with the addition of source reduction. Contaminant mass, volume, and toxicity will be reduced more rapidly than in Alternative 1. However, even if the source is substantially reduced, significantly elevated dissolved TCE concentrations may still persist for approximately 30 years, and downgradient plume migration may exceed 500 feet, depending on the actual biodegradation rate.	Source reduction simulated by the numerical model should not pose significant implementability concerns. However, long-term site management, groundwater use controls, and monitoring would be required as elevated TCE concentrations may persist for approximately 30 years. If significant plume migration occurs and completion of exposure pathways is possible, then additional remedial work may be required.	**$1,891,000**
Alternative 3 - Source Characterization - Total Source Removal - Natural Attenuation - Long-Term Monitoring - Institutional Controls	Similar to Alternative 2, with the addition of total source removal. Contaminant mass, volume, and toxicity will be reduced more rapidly than in Alternative 1. However, even if the source is completely removed, significantly elevated dissolved TCE concentrations may still persist for approximately 30 years, and downgradient plume migration may exceed 500 feet, depending on the actual biodegradation rate.	Total source removal simulated by the numerical model should not pose significant implementability concerns. However, long-term site management, groundwater use controls, and monitoring would be required as elevated TCE Concentrations may persist for approximately 30 years. If significant plume migration occurs and completion of exposure pathways is possible, then additional remedial work may be required.	**Not estimated**

Each remedial alternative is implementable and effectively reduces potential contaminant migration and toxicity in the groundwater. Each alternative should be acceptable to the public and regulatory agencies because all are protective of human health and the environment and reduce groundwater contamination; however, only Alternatives 2 and 3 address soil (source) contamination. Implementation of any one of the alternatives will require land and groundwater use controls to be enforced. Groundwater monitoring would be required for the respective projected cleanup periods.

The 30-year remediation time for Alternative 1 is considered conservative because analytical data from 1993 and 1999 indicate the plume is likely stable. Uncertainties about the nature and location of contaminant sources mean that site conditions could change during the LTM period and that additional contaminant mass could unexpecte dly enter groundwater. However, this potential drawback would apply to all alternatives and would require reevaluation in all cases. The proposed LTM period is consistent with federal recommendations that proposed or implemented remedial activities at a site should not exceed 30 years in duration (USEPA, 1988), and even if site conditions require a change in the remedial strategy it is unlikely that this time limit would be exceeded. The final evaluation criterion used to compare each of the remedial alternatives was cost; the additional costs of Alternatives 2 and 3 are justified by the risk resulting from the lack of source characterization.

Alternative 2 or 3 will reduce the level of contamination and maintain the necessary degree of protection to potential receptors at or downgradient from the site. Alternatives 2 and 3 combine natural attenuation with source reduction or removal, and provide for additional source characterization necessary to accurately predict the future behavior of dissolved contaminants at LF-03. Future exposure to potential receptors at the site can be minimized by land use restrictions. A LTM plan for groundwater, including a generic SAP, is provided for consideration in Section 7.

SECTION 7

LONG-TERM MONITORING PLAN

7.1 OVERVIEW

In keeping with the requirements of the preferred remedial alternative for F.E. Warren AFB Site LF-03, a LTM plan is herein recommended for consideration by the Base and their prime environmental contractor(s). The long-term groundwater and surface water monitoring plan for LF-03 presented in this section describes a monitoring scheme for the next 30 years for planning and budgeting purposes. It should be noted that this plan was devised on the basis of currently available data; the LTM program should be progressively revised as new data are obtained during this 30-year period. The LTM plan consists of identifying the locations of LTM wells and surface water stations, and developing a groundwater and surface water sampling and analysis strategy to accomplish the following objectives:

- Monitor changes in site conditions, including plume magnitude and extent, over time;
- Assess the effectiveness of engineered remedial actions and naturally occurring processes at reducing contaminant mass and minimizing contaminant migration;
- Assess the degree to which site-specific remediation goals (Section 6.1) are being attained and facilitate the evaluation of the need for additional remediation; and
- Verify the predictions of the numerical contaminant fate and transport model.

The strategy described in this section is designed to monitor plume migration over time and to verify that natural remedial processes are adequately protecting potential receptors. Based on the presence of an upward vertical groundwater gradient at wells 199, 199M, and 199D, surface water sampling in Crow Creek north and northeast of these wells (Figure 4.3) also is recommended to determine if the TCE plume is discharging to surface water. In the event that data collected under this LTM program indicate that planned combinations of naturally occurring processes and engineered remedial actions is insufficient to protect human health and the environment, contingency controls to more aggressively remediate the dissolved TCE plume may be necessary.

7.2 GROUNDWATER AND SURFACE WATER MONITORING NETWORK

LTM of a minimum of 31 monitoring wells located upgradient from, within, and on the periphery of the primary TCE plume is recommended. Monitoring wells include PES-1S, -2D, -3D, -4D, -5D, -6S, -6D, 62, 147, 198, 199, 199M1, 199D, 201, 203, 206, 207, 208, 209, 209M1, 209D, 210, 210M1, 210D, 211, 232, 233, 236, 237, 238, and 241

(Figure 7.1). In addition, two surface water stations also are recommended as a part of the LTM for Site LF-03.

On the basis of the contaminant transport modeling results presented in Section 6, the TCE and/or *cis*-1,2-DCE plume may migrate as far as Crow Creek (approximately 600 feet past the current downgradient plume boundary) over the next 30 years. Consequently, progressive tracking of the plume in the downgradient direction over time is recommended.

7.3 ANALYTICAL PROTOCOL

All LTM wells should be sampled and analyzed to determine compliance with chemical-specific remediation goals and to verify the effectiveness of remediation at the site. Groundwater level measurements should be made during each sampling event. Because natural attenuation is a component of the remedial strategy, appropriate geochemical parameters should also be analyzed in addition to target analytes. Groundwater samples from LTM wells should be analyzed for the parameters listed in Table 7.1.

7.4 SAMPLING FREQUENCY

Under the natural attenuation remedial strategy, dissolved TCE concentrations in excess of the 5 µg/L standard will be present for approximately 30 years. Estimated LTM costs for a 30-year period beginning in the year 2000 are presented in Section 7.5. The 31 LTM wells and 2 surface water stations should be sampled annually for 4 years beginning in 2000, and every second year for the remaining 26 years of the 30-year period. Groundwater advective velocity at the site ranges from 1.1 to 163 ft/yr, and averages 6.9 ft/yr (Table 3.1). The distance between monitoring well pair PES-6S,D at the downgradient edge of the TCE plume and downgradient well cluster 199 is approximately 450 feet (Figure 4.6). Therefore, an annual to biennial sampling frequency should be adequate to ensure that significant contaminant migration beyond well cluster 199 will not occur between sampling events, despite the fact that some dissolved contaminants will migrate faster than the advective groundwater velocity due to the effects of dispersion.

The LTM plan should be periodically reviewed and revised as appropriate on the basis of available groundwater quality data and the collection of additional source and hydrogeologic characterization data. For example, if the data collected during this time period indicate the plume has stabilized or is receding, and that CAH concentrations are diminishing, then the sampling frequency can be reduced. If sampling results indicate that geochemical conditions in the plume area are stable over time (e.g., nitrate, sulfate, and ferrous iron concentrations), then the sampling frequency for these parameters could be reduced. If the data collected at any time during the monitoring period indicate the need for additional remedial activities at the site, sampling frequency should be adjusted accordingly.

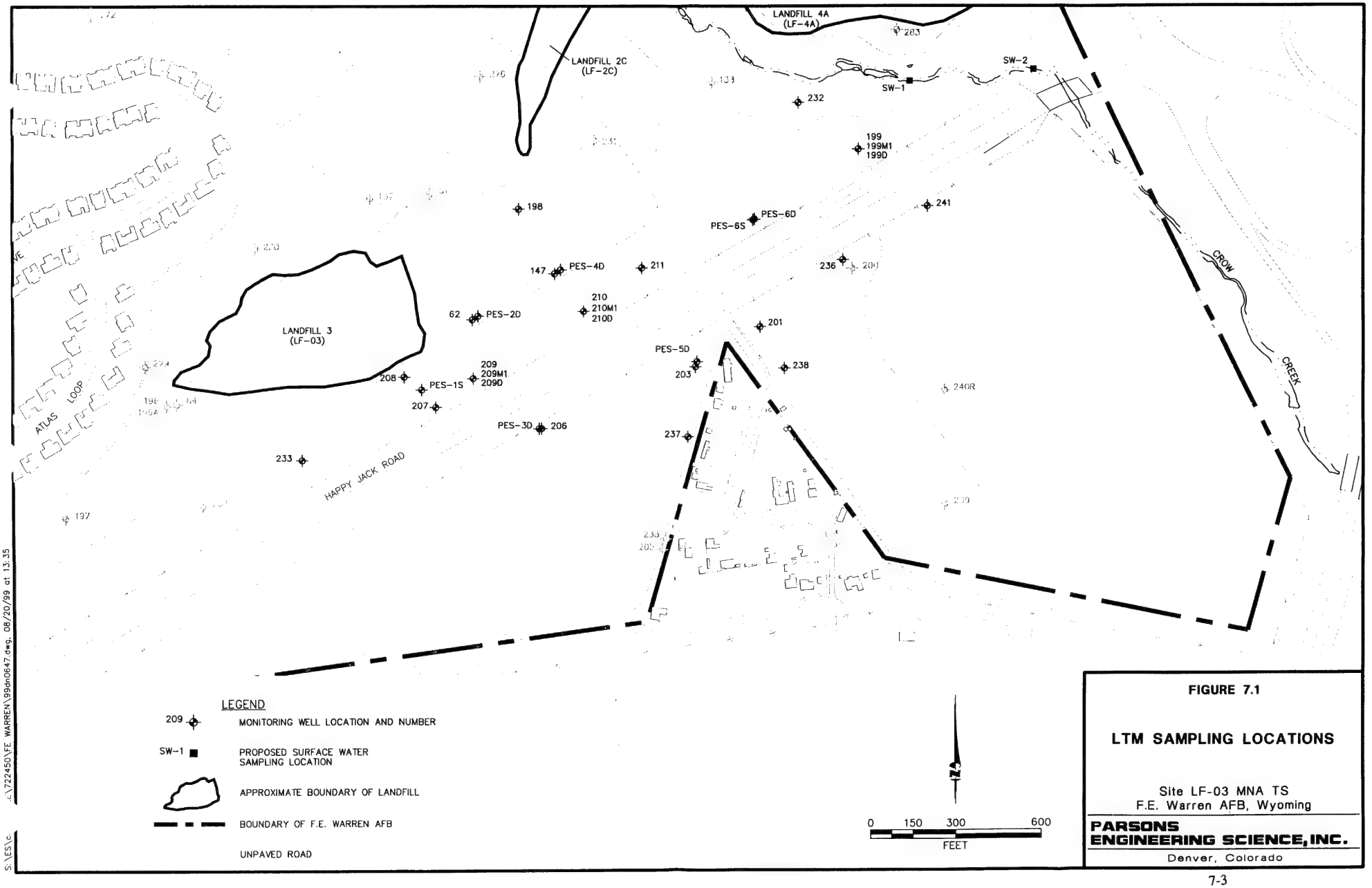

FIGURE 7.1

LTM SAMPLING LOCATIONS

Site LF-03 MNA TS
F.E. Warren AFB, Wyoming

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

S:\ES\c...\722450\FE WARREN\99dn0647.dwg, 08/20/99 at 13:35

TABLE 7.1
LONG-TERM MONITORING ANALYTICAL PROTOCOL FOR GROUNDWATER
SITE LF-03 MNA TS
F.E. WARREN AFB, WYOMING

Analyte	Method/Reference	Comments	Data Use	Recommended Frequency of Analysis	Sample Volume, Sample Container, Sample Preservation	Field or Fixed-Base Laboratory
Temperature	E170.1, direct-reading meter	Field only, measure at well-head.	Metabolism rates for microorganisms depend on temperature.	Each sampling event	Measure at well-head using a flow-through cell.	Field
Dissolved Oxygen	Dissolved oxygen meter	Measure at well-head, Refer to Method A4500 for a comparable laboratory procedure	Concentrations less than 1 mg/L generally indicate an anaerobic pathway.	Each sampling event	Collect water during purging in a flow-through cell or plastic container; analyze immediately.	Field
pH	E150.1/SW9040, direct reading meter	Measure at well-head. Protocols/ Handbook methods[a/]	Aerobic and anaerobic processes are pH-sensitive.	Each sampling event	Collect 100–250 mL of water in a glass or plastic container; analyze immediately, or measure at well-head using a flow-through cell.	Field
Conductivity	E120.1/SW9050, direct reading meter	Protocols/Handbook methods	General water quality parameter used as a marker to verify that site samples are obtained from the same groundwater system.	Each sampling event	Collect 100–250 mL of water in a glass or plastic container and analyze immediately, or measure at well-head using a flow-through cell.	Field
Redox potential	A2580 B, direct reading meter.	Measurements are made with electrodes using a meter; samples should be protected from exposure to atmospheric oxygen	The redox potential of groundwater influences and is influenced by biologically mediated reactions; the groundwater redox potential may range from 200 mV to less than -400 mV.	Each sampling event	Collect 100–250 mL of water in a glass container, filling container from bottom; analyze immediately	Field
Ferrous Iron (Fe^{2+})	Colorimetric A3500-Fe D or Colorimetric Hach® 25140-25	Field only, filter if turbid.	Elevated ferrous iron concentrations may be indicative of the anaerobic biodegradation process of iron reduction.	Each sampling event	Collect 100 mL of water in a glass container; acidify with hydrochloric acid per method	Field

TABLE 7.1 (Concluded)
LONG-TERM MONITORING ANALYTICAL PROTOCOL FOR GROUNDWATER
SITE LF-03 MNA TS
F.E. WARREN AFB, WYOMING

Analyte	Method/Reference	Comments	Data Use	Recommended Frequency of Analysis	Sample Volume, Sample Container, Sample Preservation	Field or Fixed-Base Laboratory
Nitrate	IC method E300 or method SW9056; colorimetric method E353.2.	Method E300 is a Handbook method. Method SW9056 is an equivalent procedure.	Substrate for microbial respiration if oxygen is depleted.	Each sampling event	Collect up to 40 mL of water in a glass or plastic container; cool to 4°C	Fixed-base
Sulfate (SO_4^{2-})	IC method E300 or method SW9056 or Hach® SulfaVer 4 method	Method E300 is a photometric Handbook method; method SW9056 is an equivalent procedure.	Substrate for anaerobic microbial respiration	Each sampling event	Collect up to 40 mL of water in a glass or plastic container; cool to 4°C	Fixed-base or field (for Hach® method)
Methane, Ethane, and Ethene	RSKSOP-114 modified to analyze water samples for methane by headspace sampling with dual thermal conductivity and flame ionization detection.	Method published and used by the USEPA Robert S. Kerr Laboratory	The presence of methane indicates the presence of sufficiently reducing conditons for reductive dehalogenation to occur	Each sampling event	Collect water samples in 40 mL volatile organic analysis (VOA) vials with butyl gray/Teflon-lined caps (zero headspace); cool to 4°C	Fixed-base
Volatile Organics	GC/MS method 8260B	Handbook method	Measured for regulatory compliance	Each sampling event	Collect water samples in a 40 mL VOA vial; cool to 4°C; add hydrochloric acid to pH < 2	Fixed-base

[a] Protocol analytical methods are those presented by Wiedemeier *et al.* (1995). Handbook refers to "AFCEE Handbook to Support the Installation Restoration Program (IRP) Remedial Investigation/Feasibility Study (RI/FS).

7.5 LTM COST ESTIMATE

The estimated present worth cost for the LTM program described in the preceding sections is shown in Table 7.2. Included in the total cost of $1,609,300 are performing the recommended groundwater and surface water monitoring, maintaining institutional controls, public education, project management, and reporting.

TABLE 7.2
ESTIMATED LTM COSTS
SITE LF-03 RNA TS
F.E. WARREN AFB, WYOMING

Monitoring Costs	Total Cost
Conduct Annual Groundwater Monitoring at 31 Wells and Surface Water Monitoring at 2 Stations from 2000 to 2004.	$194,400
Conduct Biennial Groundwater Monitoring at 31 Wells and Surface Water Monitoring at 2 Stations from 2005 to 2029.	$974,700
Site Management (Maintain Institutional Controls/Public Education) and Reporting (30 years)	$440,300
Total Cost of LTM Program	**$1,609,000**

Note: Cost assumes that LTM will be performed by local (Cheyenne area) personnel.

SECTION 8

CONCLUSIONS AND RECOMMENDATIONS

This report presents the results of a TS conducted to evaluate the use of natural attenuation for remediation of CAH-contaminated groundwater at Site LF-03, F.E. Warren AFB, Wyoming. The numerical models MODFLOW and MT3D were used in conjunction with site-specific geologic, hydrologic, and laboratory analytical data to simulate the migration and biodegradation of TCE dissolved in groundwater. To obtain the data necessary for this natural attenuation demonstration, soil and groundwater samples were collected from the site and analyzed. Physical and chemical data collected under this program were supplemented (where necessary) with data collected during previous site characterization events.

It is likely that contaminants were first introduced into groundwater at this site shortly after the opening of LF-03 in 1960. Solvents, fuels, and other liquid wastes may have been spilled or dumped, or have leaked from containers in the landfill. Contaminants dissolved in leachate are assumed to have entered groundwater over relatively large areas (i.e., the landfill), through point sources due to spills or dumping, or through contact between groundwater and residual NAPL at or below the water table.

Contaminants observed in groundwater at LF-03 at concentrations greater than USEPA MCLs include TCE and *cis*-1,2-DCE. The dissolved CAH plume appears to have migrated approximately 1,500 feet northeast of the source area at LF-03. Comparison of TCE plumes delineated in 1993 and 1999 indicate that the TCE plume is at steady state, although TCE concentrations have increased at several locations within the plume.

Several lines of chemical and geochemical evidence indicate that, although dissolved TCE at LF-03 is undergoing biologically facilitated reductive dehalogenation, the occurrence of this process is limited and localized. Near the source area, the occurrence of reductive dehalogenation is most clearly indicated by a decreasing ratio of TCE to the primary metabolite *cis*-1,2-DCE.

Downgradient from the source area, increasing TCE to DCE ratios suggest that DCE is degraded through oxidation reactions, while TCE mass is relatively unaffected by destructive attenuation mechanisms. As a result, the parent CAH (TCE) still comprises the majority of the contamination present in groundwater throughout most of the plume. The dissolved CAH plume at LF-03 exhibits characteristics of predominantly Type 3 behavior, with some indications of Type 1 behavior evidenced in and immediately downgradient from the source area. The evidence supporting the limited occurrence of TCE biodegradation is summarized below.

- The presence of *cis*-1,2-DCE is a direct indication that TCE is being reductively dehalogenated, but increasing TCE to DCE ratios with distance from the source indicate that reductive transformation of TCE is limited to the approximate point of release;

- The presence of elevated chloride concentrations (above background levels) is very localized, indicating that reductive dehalogenation reactions are not prevalent enough in many portions of the plume to significantly influence chloride concentrations;

- ORP data indicate that the groundwater is sufficiently reducing to support the occurrence of reductive dehalogenation (via denitrification or manganese reduction), but redox conditions are not optimal for this process;

- The lack of true anaerobic conditions throughout the majority of the TCE plume limits the occurrence of reductive dehalogenation, which is an anaerobic process;

- Nitrate and sulfate concentrations within the plume area are sufficiently high that use of CAHs as electron acceptors may be inhibited due to the preferential use of these anions as alternate electron acceptors; and

- The evidence that methanogenic conditions existed near the source area indicates that conditions favorable for reductive dehalogenation of CAHs were at least locally present; however, methane was infrequently detected and, where present, occurred at very low concentrations, indicating that the occurrence of methanogenesis was spatially and temporally very limited.

Anaerobic conditions in the source area may be driven by low concentrations of anthropogenic fuel hydrocarbons. Downgradient from the source area, reductive dehalogenation ceases, and *cis*-1,2-DCE produced in the source area likely is aerobically biodegraded. VC has not been detected, indicating no reductive dehalogenation of *cis*-1,2-DCE downgradient from the source area. c*is*-1,2-DCE persists with TCE to the leading edge of the shallow groundwater plume.

Rates of total chlorionated ethene biodegradation estimated from data collected for this demonstration range from 6.96E-05 day^{-1} (half-life of 27 years) to 1.77E-06 day^{-1} (half-life of 1,073 years). The higher rate includes all degradation processes at the site, while the lower rate include reductive dechlorination only. Because aerobic or abiotic degradation of *cis*-1,2-DCE is likely at this site, the higher biodegradation rate is considered more representative for this site.

Site-specific hydrogeologic and laboratory analytical data were used in the numerical groundwater model to simulate the effects of advection, dispersion, sorption, and biodegradation on the fate and transport of the TCE plume. TCE is used as an indicator compound in this report due to its relatively high concentration, low MCL, and persistence downgradient from the source area. During model calibration, model parameters that could not be obtained from existing site data were estimated using common literature values for aquifer materials similar to those found at the site. Model

predictions were found to be sensitive to hydraulic conductivity, effective porosity, dispersivity, and the magnitude of the first-order TCE decay rate.

Remedial Alternative 1 incorporates natural attenuation, but does not include engineered remediation. The model used to simulate this alternative incorporates the assumption that dissolution from leachate or residual NAPL in the source area into groundwater will naturally decrease at a geometric rate of 7.3 percent per year (each concentration was decreased by a factor equal to 7.3 percent of the previous year's concentration, as estimated by model calibration) during the 30-year predictive period. The results of the model indicate, over the next 30 years that TCE will migrate an additional 500 feet from the present plume toe to Crow Creek. However, concentrations of TCE discharging to Crow Creek are predicted to be less than 5 ug/L. Furthermore, maximum concentrations of TCE dissolved in groundwater are predicted to decrease to approximately 10 µg/L over the same 30-year period.

The model used to simulate remedial Alternative 2 assumes that partial source removal via application of engineered remedial technologies such as excavation would reduce TCE source mass. This model incorporates the assumption that the remediation will reduce the TCE source at a geometric rate of 50 percent per year over a 2-year period, followed by a 7.3 percent per year reduction due to natural weathering for the remainder of the 30-year model simulation. Results of this model indicate that source reduction at the assumed rates would result in only slightly more rapid reduction in dissolved TCE concentrations within the plume relative to Alternative 1. The Alternative 2 model predicts that maximum TCE concentrations would be reduced more rapidly near the source area, but not in downgradient portions of the plume. The overall plume extent would not be reduced, and TCE concentrations would continue to persist as with Alternative 1.

The model used to simulate remedial Alternative 3 is similar to the Alternative 2 model, but assumes total source removal. The model was run with all source terms removed as of 1999 to simulate a total source removal scenario. Results are similar to Alternative 2; however the TCE plume is further reduced near the source area. Maximum TCE concentrations would be reduced more rapidly near the source area, but not in the downgradient portions of the plume. The overall plume extent would be reduced near the source area, and TCE concentrations would continue to persist.

The contaminant source at Site LF-03 has not been well characterized. Therefore, the numerical models may not be accurately simulating the future strength and persistence of the source. For this reason, AFCEE recommends that additional source characterization activities (e.g., soil gas survey on a tight grid spacing) be performed to identify any remaining significant release areas. If source areas that could significantly contribute to the future magnitude and persistence of the dissolved CAH plume are identified, then consideration should be given to their remediation (e.g., via excavation). The remaining residual and dissolved contamination could then be left to naturally attenuate over time.

In any case, future exposure to potential receptors at the site can be minimized by land use restrictions, because access to the Base (and hence most of the site) is controlled by Base security. The degree to which RNA will continue to control significant

downgradient migration of the plume is not known with certainty, but will become more apparent as successive LTM sampling events are performed.

To assess the effectiveness of both naturally-occurring processes and source removal at reducing contaminant mass and minimizing contaminant migration, groundwater from a minimum of 29 existing monitoring wells and 2 surface water stations are recommended to be sampled annually for 4 years to build a historical groundwater quality database for the site. Following completion of the 4-year annual LTM period, the LTM program should be reassessed, and sampling frequency may be reduced to biennial events. The existing monitoring well network should be adequate to document trends in the concentration and distribution of both the TCE and *cis*-1,2-DCE plumes.

The LTM plan should be periodically reviewed and revised as appropriate on the basis of available groundwater quality data. For example, if sampling results demonstrate that the plume is in equilibrium (not migrating downgradient) or is receding toward the source area, then the sampling frequency and number of monitoring locations could be reduced appropriately. If the data collected at any time during the monitoring period indicate the need for additional remedial activities at the site, sampling frequency should be adjusted accordingly and appropriate remedial actions (e.g., interceptor trench or injection of carbon source to induce reductive dehalogenation as described in Section 6) could be evaluated.

SECTION 9

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APPENDIX A

SELECTED FIGURES AND TABLES FROM THE PHASE I RCRA RFI FOR LF-03 (IT, 1994), AND THE DRAFT RCRA RFI FOR LF-03 (TT, 1996)

Table 2-2. Physical properties of soil, landfill 3, F.E. Warren Air Force Base, Wyoming, 1993

[ft, feet; lb/ft^3, pound per cubic foot; ft/d, foot per day; NM, not measured; BWT, below water table, November 1993]

Test-hole number	Interval sampled below land surface (ft)	Dry bulk density (lb/ft^3)	Moisture content (weight percent)	Porosity (percent)	Vertical hydraulic conductivity (ft/d)	Plastic limit (percent)	Liquid limit (percent)
T139	10-11	88.4	13.5	45.3	NM	16.4	23.2
	16-17	91.9	17.9	43.5	NM	16.9	25.7
	25-26	NM	NM	NM	NM	NM	NM
	38-39	70.8	BWT	58.1	$1x10^{-3}$	BWT	BWT
	44-45	75.4	BWT	55.6	$3.1x10^{-3}$	BWT	BWT
	50-51	99.1	BWT	38.5	NM	BWT	BWT
	72-73	90.7	BWT	45.4	$5.8x10^{-3}$	BWT	BWT
	77-78	101.5	BWT	37.7	$1.2x10^{-5}$	BWT	BWT
	87-88	88.6	BWT	45.2	$5.6x10^{-3}$	BWT	BWT
	92-93	NM	BWT	NM	NM	BWT	BWT

Table 2-3. Results of aquifer tests, landfill 3, F.E. Warren Air Force Base, Wyoming,

[NA, not available; --, not calculated because insufficient water in well bore]

Monitor-well number and depth of well (feet)	Screened interval (feet below land surface)	Predominant lithology at screened interval	Horizontal hydraulic conductivity in feet per day
63	14-29	NA	[1]11.5
64	29-44	NA	10
137	23-38	NA	22
147	13-28	NA	19
196	84-94	Silt, clay	.1
196A	46.5-56.5	Sand	3
197	24.5-39.5	Sand, silt	--
198	22-34.5	Silt	2
199	4.5-19.5	Sand	40
201	4.5-19.5	Sand	.003
203	4.5-19.5	Clay, sand	.008
206	4.7-19.7	Sand	49
207	14.4-29.4	Sand	38
208	30.5-45.5	Sand	92
209	13-23	Silt	21
210	8-23	Silt	1.2
211	9.3-24.3	Clay, sand	1
229	24.8-34.8	Sand	--
230	27.5-42.5	Sand, gravel	82
231	12.5-27.5	Silt	24
232	7.5-20	Sand, silt	4
233	25.5-40.5	Silt	20
234	22.5-37.5	Silt, sand	42
235	10.5-25.5	Claystone	1
236	12.5-27.5	Sand	.003

[1]Value for monitor well 63 from the IRP RI (U.S. Air Force, 1991, p.205, 210). Monitor well 63 was destroyed in 1988.

Test-Well Installation and Sampling Data

Table A-2. Test-well installation and ground-water sampling data, landfill 3, F.E. Warren Air Force Base, Wyoming, 1993

[If a test well was redrilled because it was dry at the original depth, the depth of the redrilled well, the depth to water, and the height of water are listed as the second entry in the appropriate column. --, not applicable]

Test-well number	Date drilled	Depth of well (feet below land surface)	Screened interval (feet below land surface)	Date sampled	Date redrilled	Depth to water (feet below land surface)	Height of water in well (feet above bottom)	Date resampled
[1]HP-LF3-01	06-30-93	35	31.5-35	07-01-93	--	29.81	5.19	--
[2]HP-LF3-02	07-01-93	32	27-32	07-01-93	--	--	--	--
		35	--	--	07-01-93	30.23	4.78	07-01-93
[2]HP-LF3-03	07-01-93	30	30-30	07-02-93	--	--	--	--
		40	--	--	07-02-93	30.35	9.65	07-02-93
HP-LF3-04	07-02-93	33	23-33	07-06-93	--	--	--	--
		37	27-37	--	07-06-93	35.88	1.12	07-06-93
HP-LF3-05	07-06-93	35	25-35	07-09-93	--	--	--	--
			25-35	--	07-07-93	31.85	3.15	07-07-93
HP-LF3-06	07-07-93	30	20-30	07-09-93	--	20.82	9.12	--
HP-LF3-07	07-07-93	38	28-38	07-08-93	--	--	--	--
			28-38	--	07-08-93	36.65	1.35	07-08-93
HP-LF3-08	07-08-93	38	28-38	07-09-93	--	33.90	4.10	--
HP-LF3-09	07-08-93	29	24-29	07-09-93	--	23.20	5.80	--
HP-LF3-10	07-09-93	38	33-38	07-12-93	--	30.67	7.33	--
HP-LF3-11	07-09-93	32	27-32	07-13-93	--	31.04	.96	--
HP-LF3-12	07-09-93	38	33-38	07-12-93	--	23.14	14.86	--
HP-LF3-13	07-19-93	24.8	14.8-24.8	07-21-93	--	17.11	7.69	--
HP-LF3-14	07-19-93	17.4	7.4-17.4	07-21-93	--	13.78	3.62	--
HP-LF3-15	07-20-93	33	23-33	07-21-93	--	12.04	20.96	--
HP-LF3-16	07-20-93	32.5	22.5-32.5	07-21-93	--	7.85	24.65	--
HP-LF3-17	07-12-93	32.5	27.5-32.5	07-13-93	--	15.90	16.6	--
HP-LF3-18	07-12-93	32.5	27.5-32.5	07-13-93	--	23.69	8.81	--
HP-LF3-19	07-13-93	32.5	27.5-32.5	07-16-93	--	29.72	2.78	--
HP-LF3-20	08-16-93	37.1	27.1-37.1	08-17-93	--	35.15	1.95	--
HP-LF3-21	08-16-93	44.2	34.2-44.2	08-17-93	--	32.89	11.31	--
HP-LF3-22	08-17-93	36.8	26.8-36.8	08-17-93	--	33.40	3.40	--
HP-LF3-23	08-17-93	31.6	21.6-31.6	08-17-93	--	27.39	4.21	--
HP-LF3-24	08-17-93	27.8	17.8-27.8	08-17-93	--	25.54	2.26	--

Table A-2. Test-well installation and ground-water sampling data, landfill 3, F.E. Warren Air Force Base, Wyoming, 1993--Continued

Test-well number	Date drilled	Depth of well (feet below land surface)	Screened interval (feet below land surface)	Date sampled	Date redrilled	Depth to water (feet below land surface)	Height of water in well (feet above bottom)	Date resampled
HP-LF3-25	08-17-93	28.6	18.6-28.6	08-18-93	--	23.89	4.71	--
HP-LF3-26	08-17-93	28.8	18.8-28.8	08-18-93	--	15.33	13.47	--
HP-LF3-27	08-17-93	20.5	10.5-20.5	08-18-93	--	11.63	8.87	--
HP-LF3-28	08-17-93	10	0-10	08-18-93	--	8.24	1.76	--
HP-LF3-29	08-16-93	17	7-17	08-17-93	--	11.89	5.11	--
HP-LF3-30	08-16-93	22.5	12.5-22.5	08-17-93	--	19.97	2.53	--
HP-LF3-31	08-16-93	17.5	7.5-17.5	08-17-93	--	9.51	7.99	--
HP-LF3-32	08-16-93	17.5	7.5-17.5	08-17-93	--	7.89	9.61	--
HP-LF3-33	08-16-93	17.5	7.5-17.5	08-17-93	--	9.4	8.1	--
HP-LF3-34	08-16-93	18	8-18	08-17-93	--	11.52	6.48	--
HP-LF3-35	08-16-93	27.5	17.5-27.5	08-17-93	--	25.07	2.43	--
HP-LF3-36	08-16-93	27.5	17.5-27.5	08-17-93	--	24.55	2.95	--
HP-LF3-37	08-18-93	34.5	24.5-34.5	08-18-93	--	32.07	2.43	--
HP-LF3-38	08-18-93	38.6	28.6-38.6	08-18-93	--	34.37	4.23	--
HP-LF3-39	08-16-93	39	29-39	08-17-93	--	30.82	8.18	--
HP-LF3-40	08-16-93	38.8	28.8-38.8	08-17-93	--	32.08	1.72	--
HP-LF3-41	08-16-93	17.5	7.5-17.5	08-17-93	--	9.41	8.09	--
HP-LF3-42	08-17-93	17.5	7.5-17.5	08-17-93	--	9.99	7.51	--
HP-LF3-43	08-17-93	28	18-28	08-17-93	--	16.57	11.43	--
HP-LF3-44	08-16-93	9	0-9	08-17-93	--	6.3	2.70	--
HP-LF3-45	08-16-93	27.5	17.5-27.5	08-17-93	--	--	--	--
			17.5-27.5	--	08-17-93	24.93	2.57	08-18-93
HP-LF3-46	09-27-93	15	5-15	08-28-93	--	10.31	4.69	--
HP-LF3-47	09-25-93	35	25-35	08-28-93	--	28.1	6.90	--
HP-LF3-48	09-25-93	36	26-36	08-28-93	--	31.09	4.91	--
HP-LF3-49	09-25-93	38.3	28.3-38.3	08-28-93	--	33.63	4.67	--

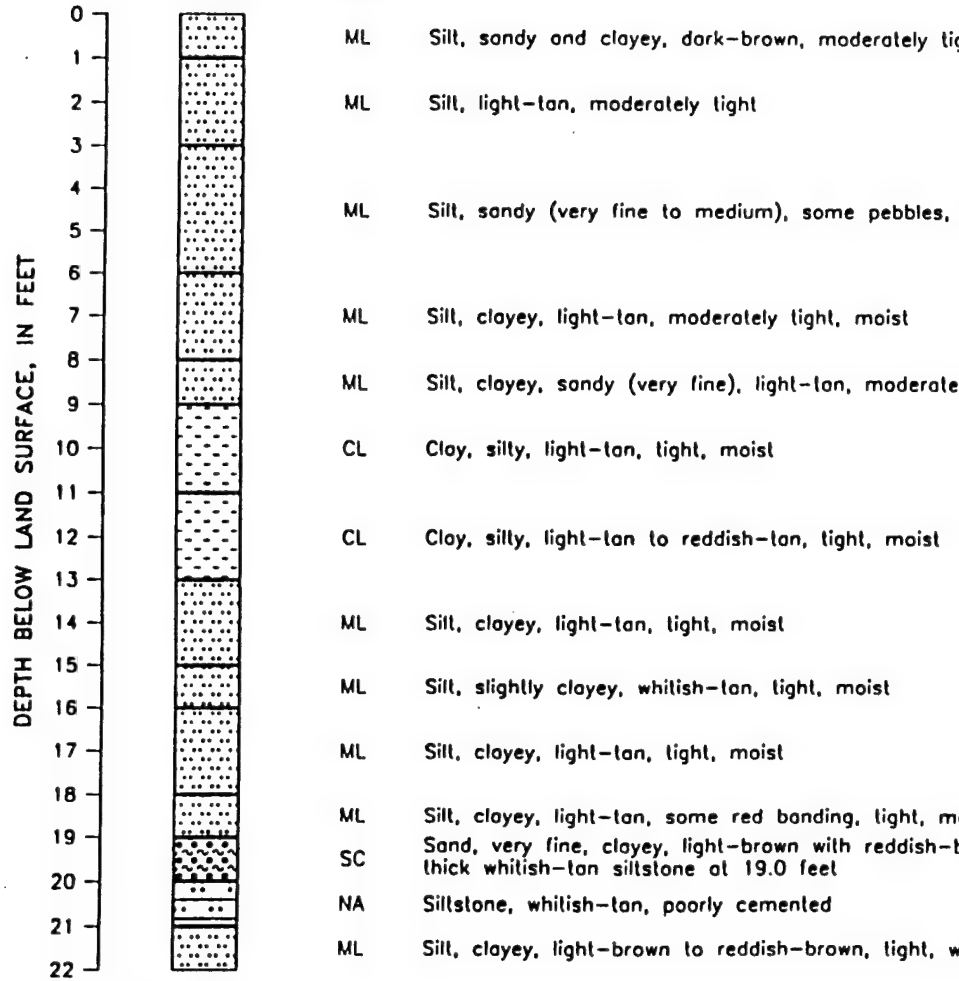
[1] Test well was driven with a hydropunch system.

[2] Test well was drilled to about two feet above the estimated water table, and then was driven to about five feet below the water table with a hydropunch system.

Monitor-Well Lithology and Construction Data

WELL 196

LAND SURFACE ELEVATION 6,165.60 FEET ABOVE SEA LEVEL



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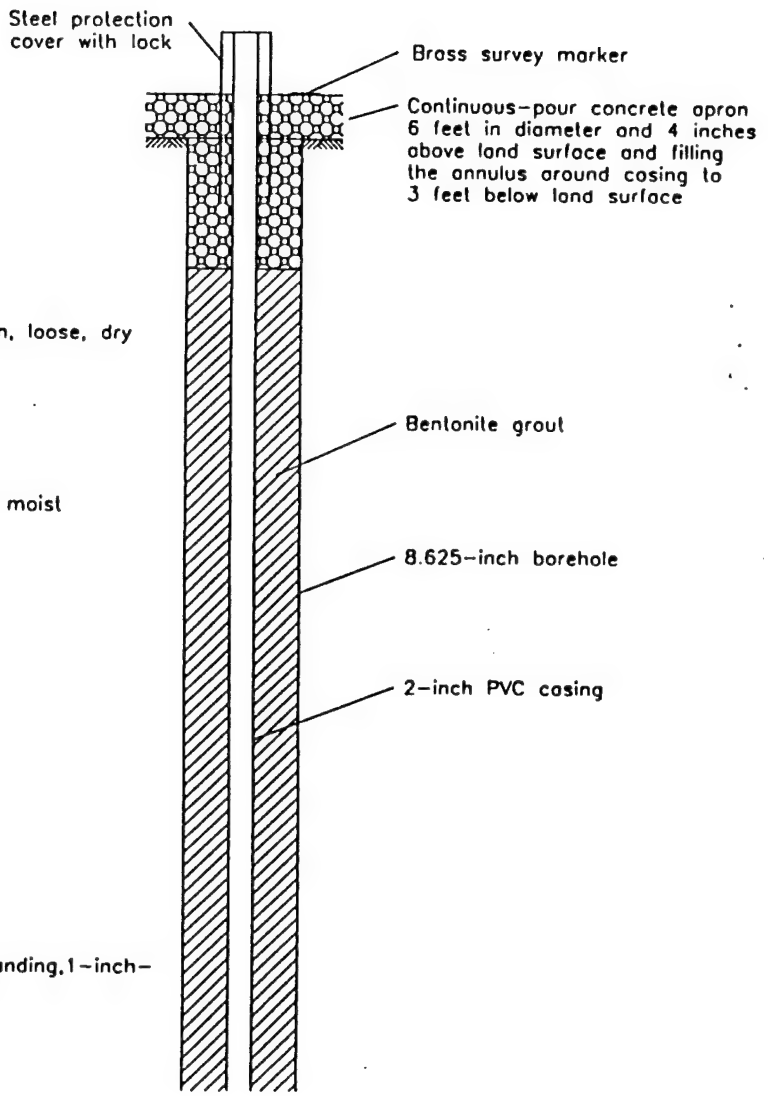
WELL CONSTRUCTION



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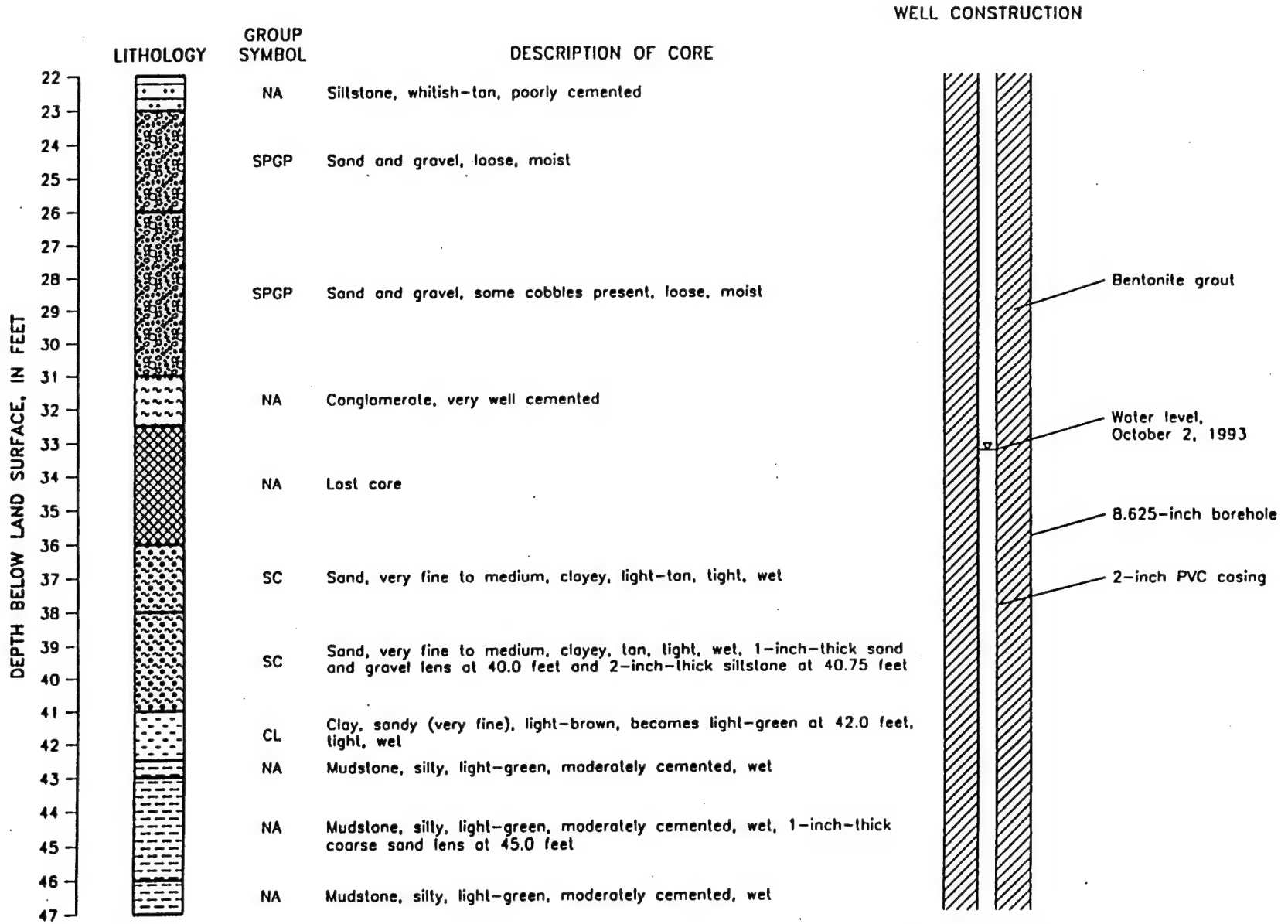
WELL 196--Continued



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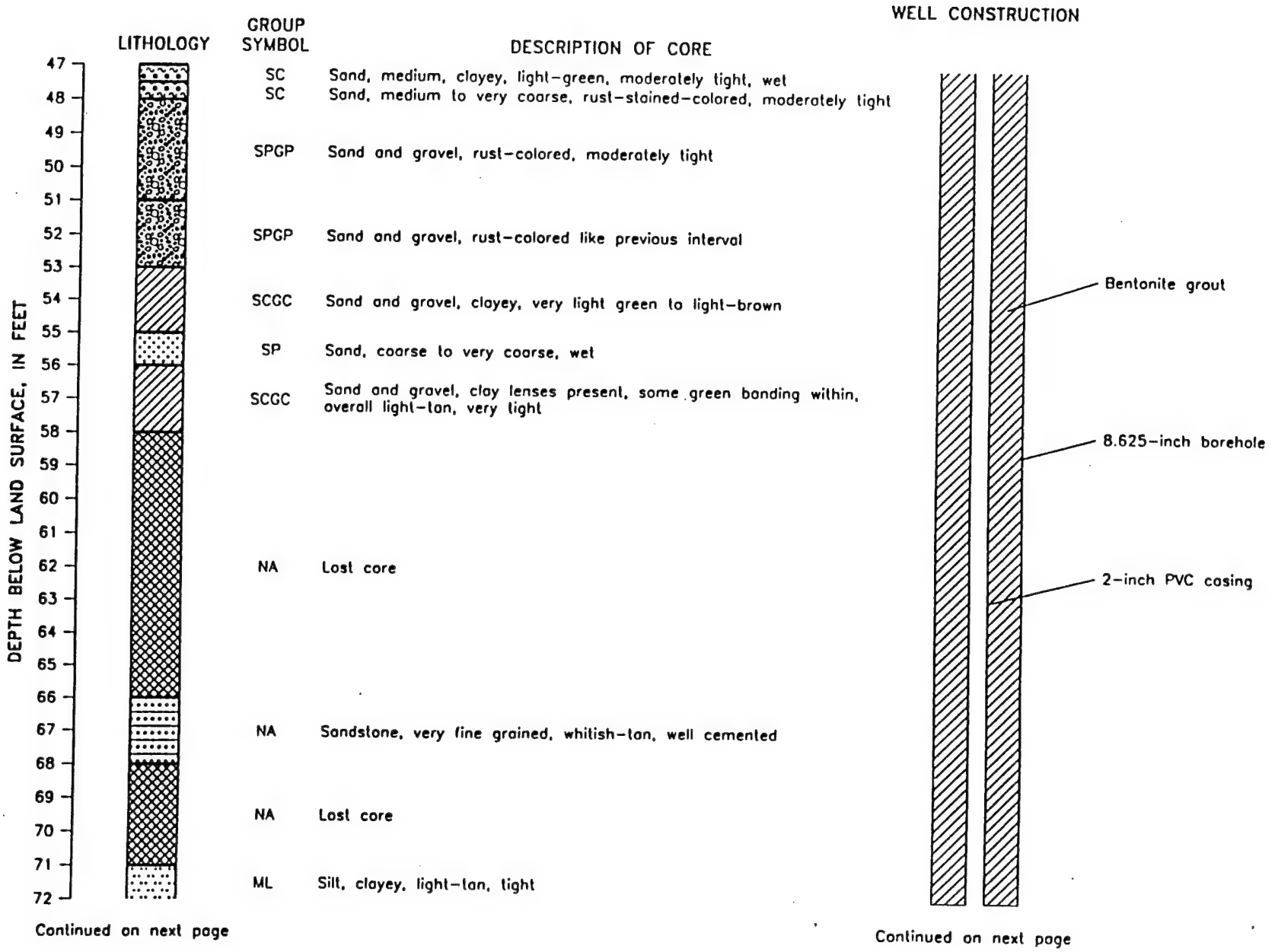
WELL 196--Continued



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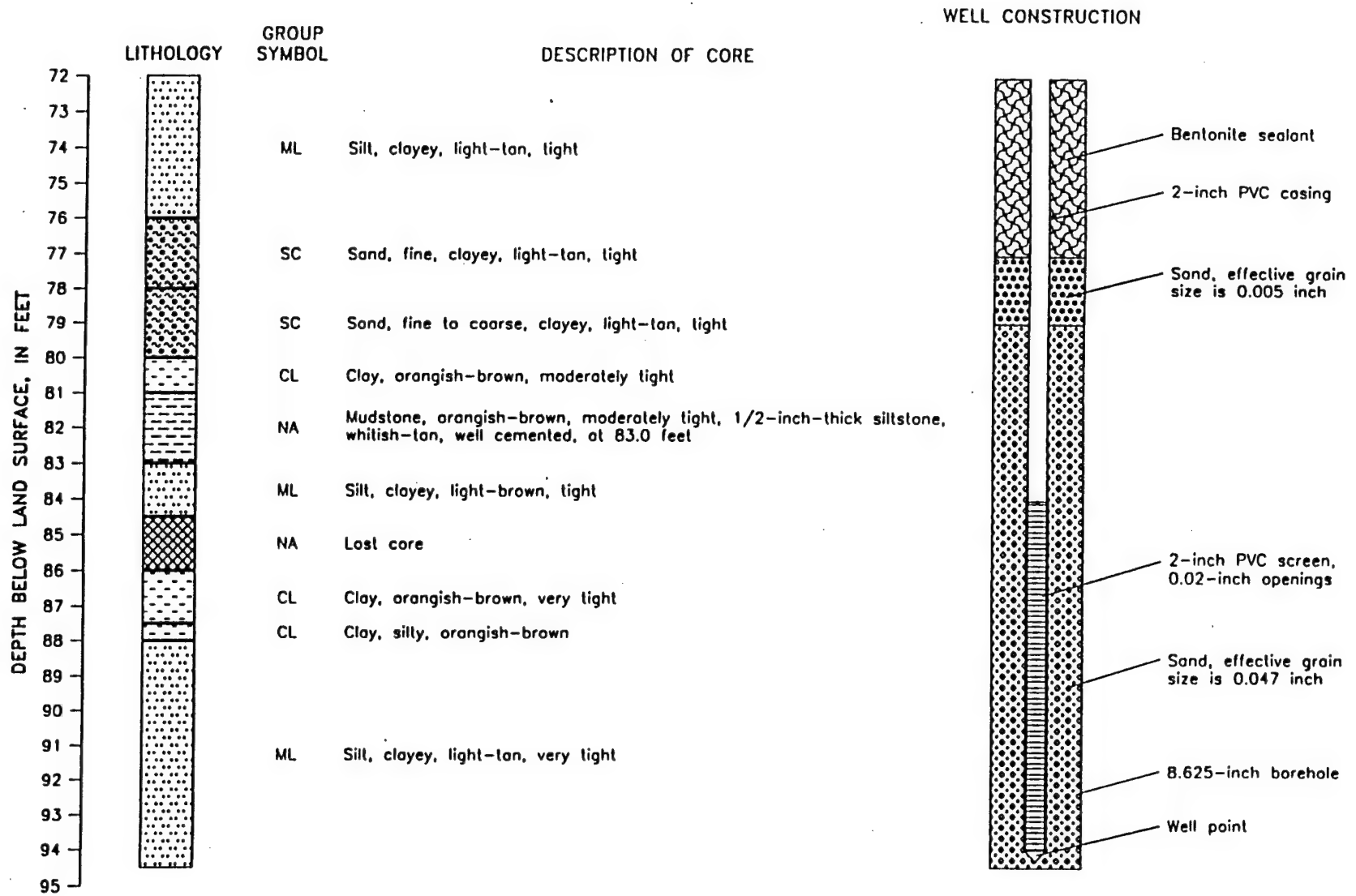
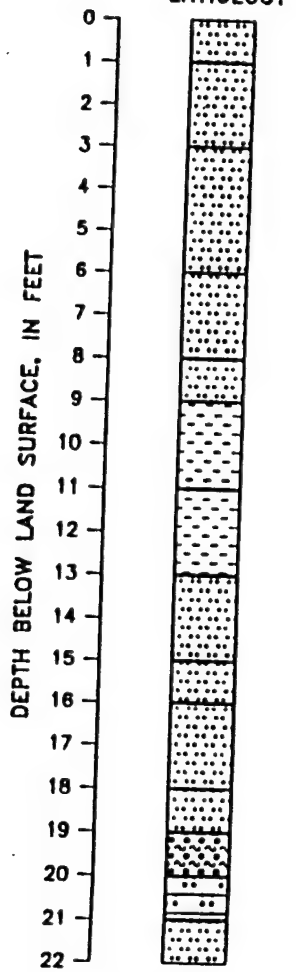


WELL 196A

LAND SURFACE ELEVATION 6,165.60 FEET ABOVE SEA LEVEL



GROUP SYMBOL	DESCRIPTION OF CORE FROM WELL 196
ML	Silt, sandy and clayey, dark-brown, moderately tight
ML	Silt, light-tan, moderately tight
ML	Silt, sandy (very fine to medium), some pebbles, light-tan, loose, dry
ML	Silt, clayey, light-tan, moderately tight, moist
ML	Silt, clayey, sandy (very fine), light-tan, moderately tight, moist
CL	Clay, silty, light-tan, tight, moist
CL	Clay, silty, light-tan to reddish-tan, tight, moist
ML	Silt, clayey, light-tan, tight, moist
ML	Silt, slightly clayey, whitish-tan, tight, moist
ML	Silt, clayey, light-tan, tight, moist
ML	Silt, clayey, light-tan, some red banding, tight, moist
SC	Sand, very fine, clayey, light-brown with reddish-brown banding, 1-inch-thick whitish-tan siltstone at 19.0 feet
NA	Siltstone, whitish-tan, poorly cemented
ML	Silt, clayey, light-brown to reddish-brown, tight, wet

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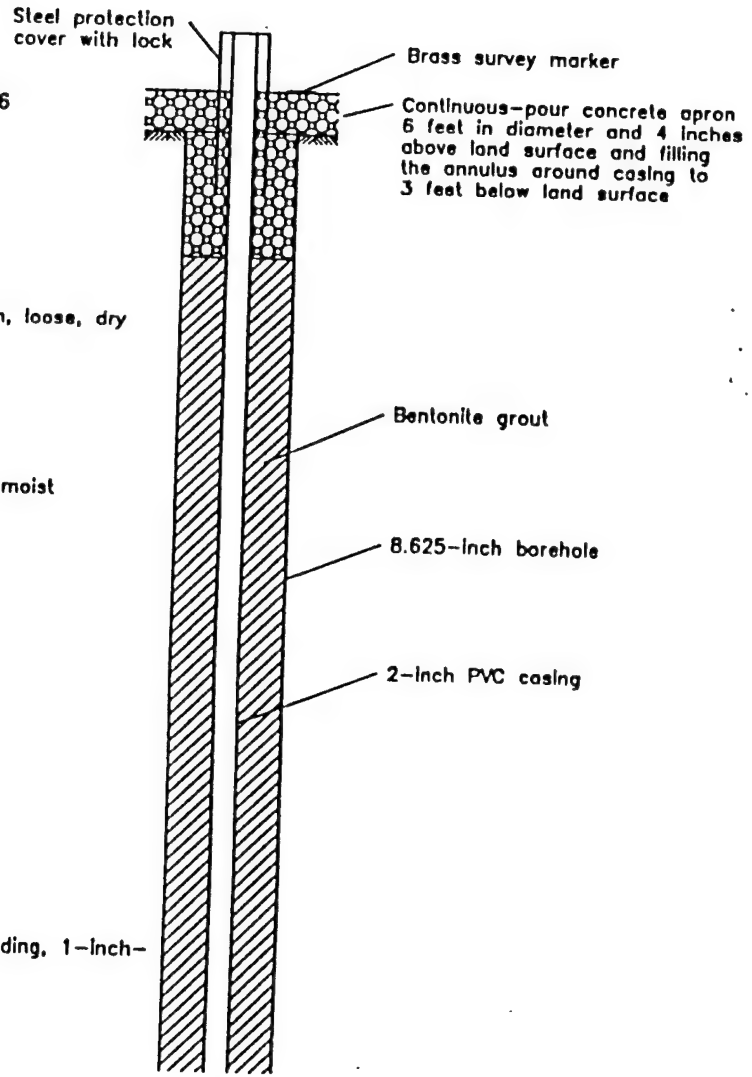
WELL CONSTRUCTION



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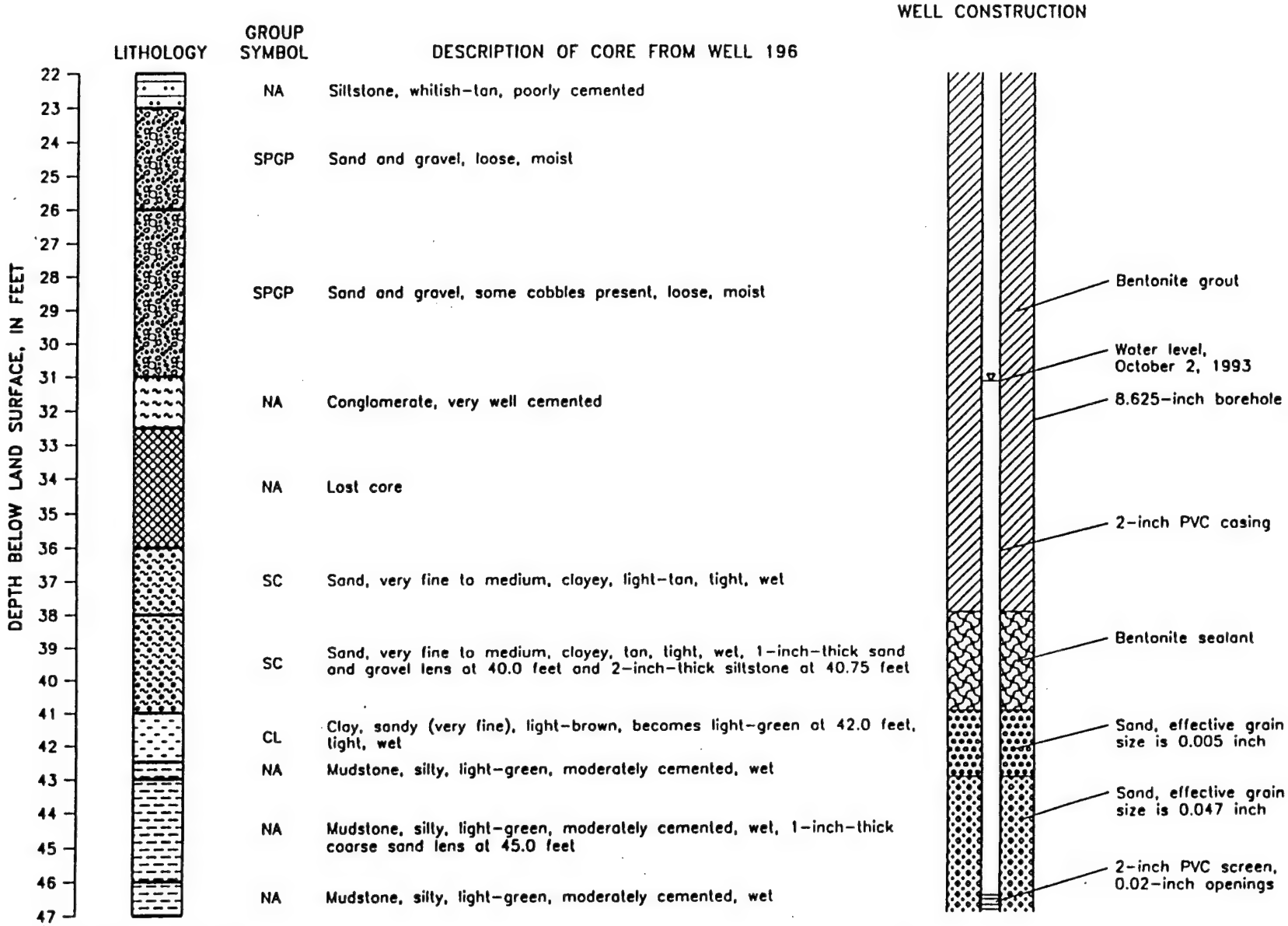

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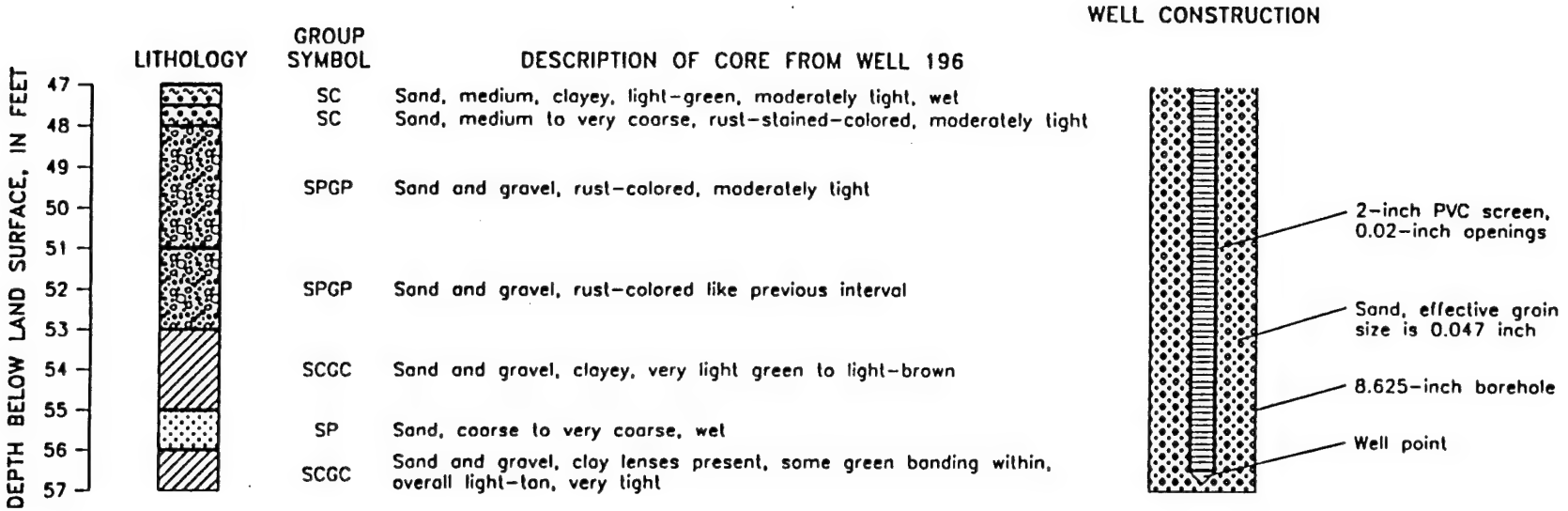
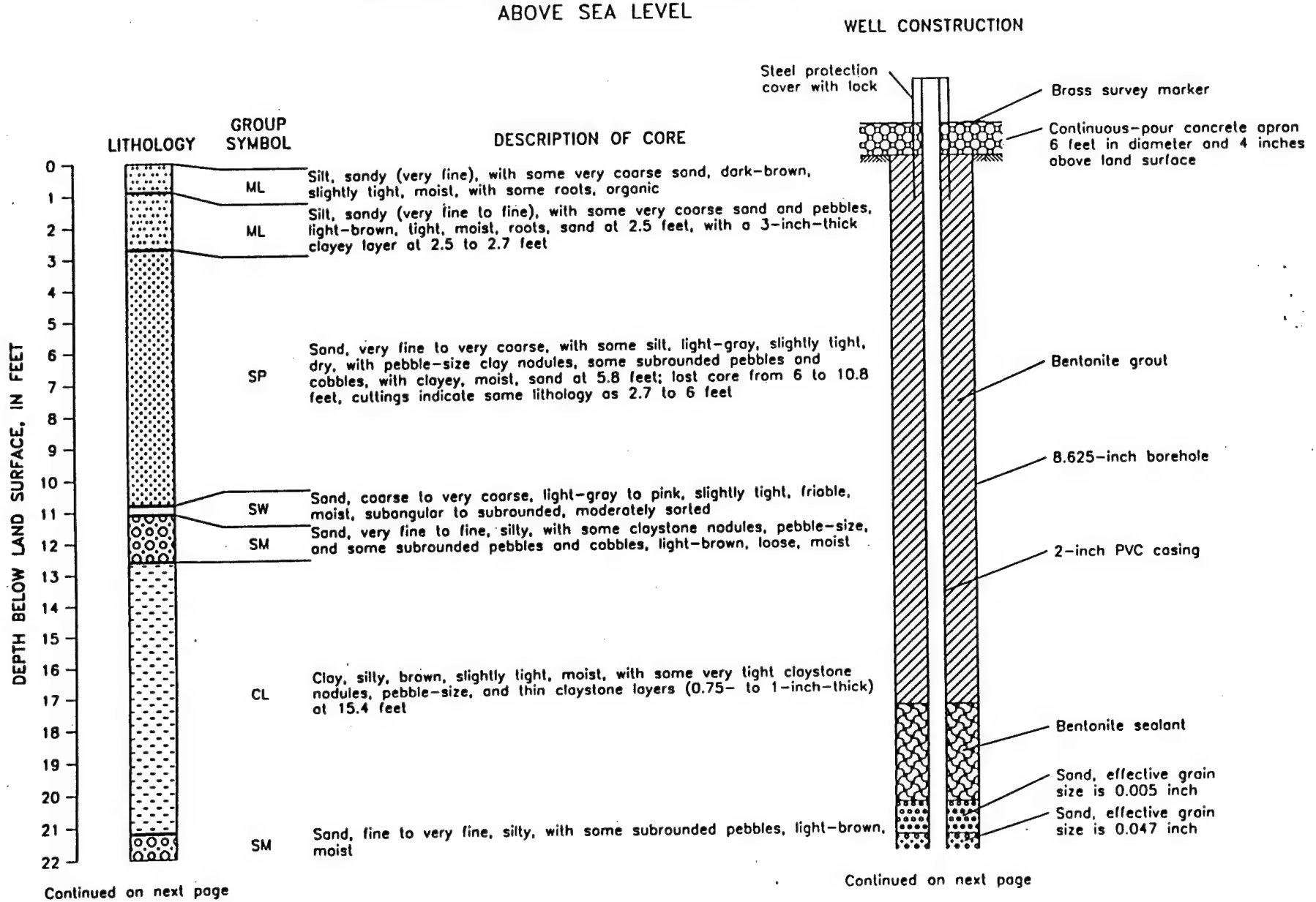
WELL 196A--Continued

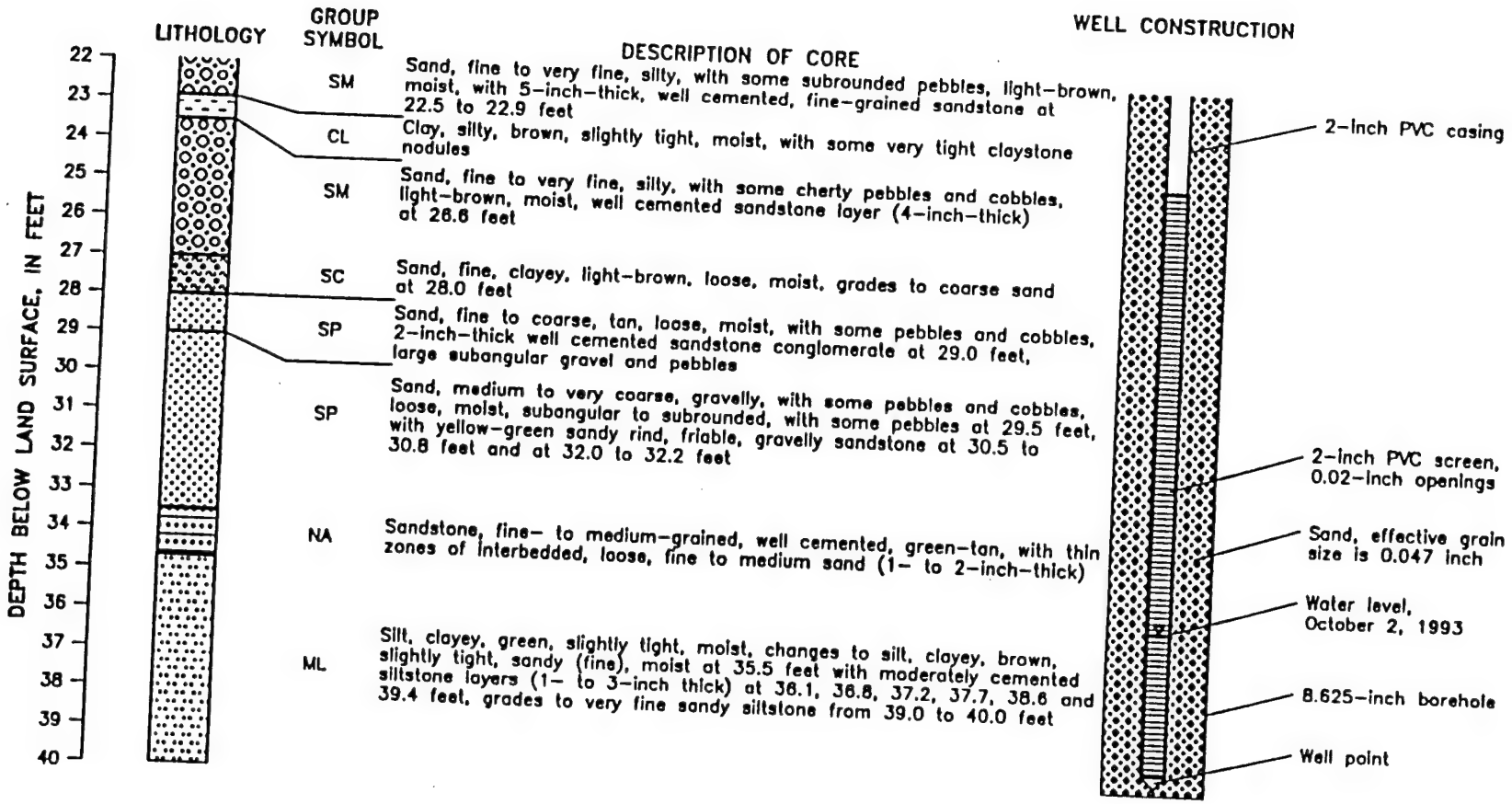


WELL 197

LAND SURFACE ELEVATION 6,174.25 FEET ABOVE SEA LEVEL

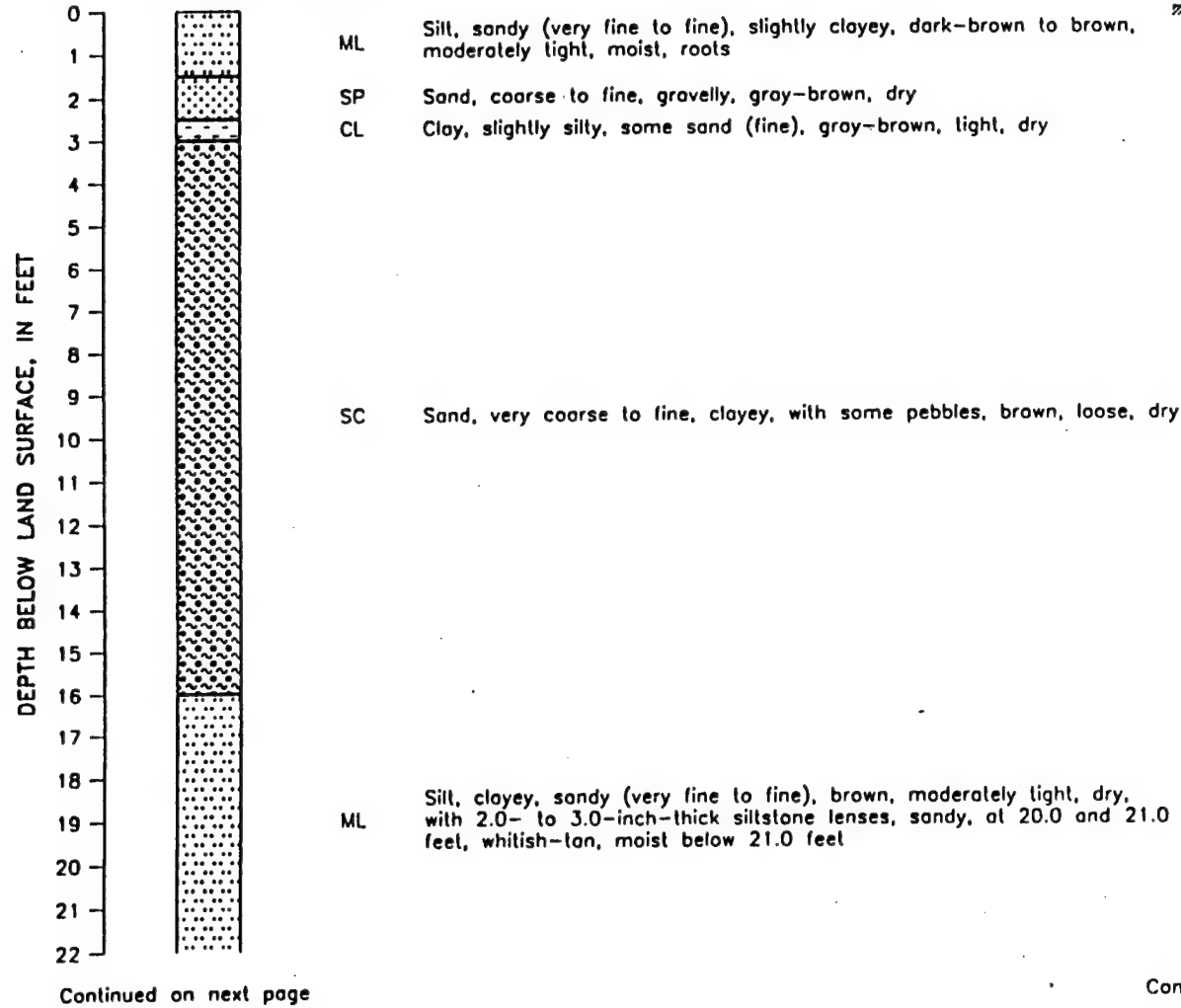


WELL 197--Continued



WELL 198

LAND SURFACE ELEVATION 6,141.20 FEET ABOVE SEA LEVEL



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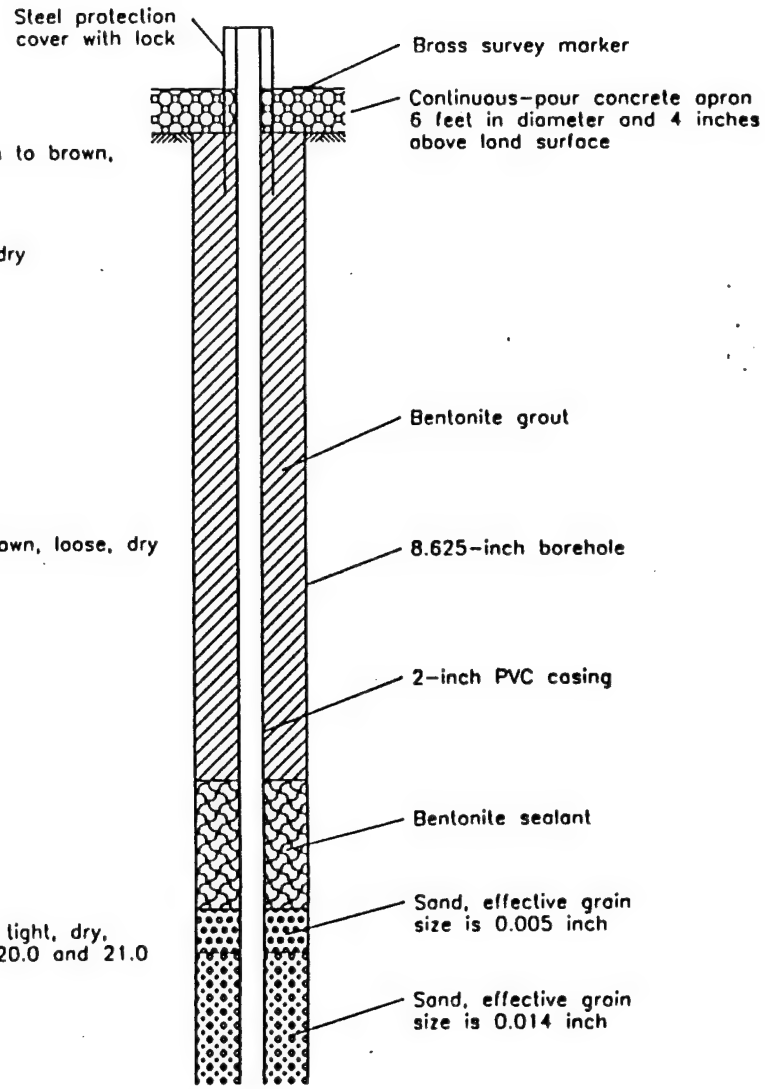
WELL CONSTRUCTION



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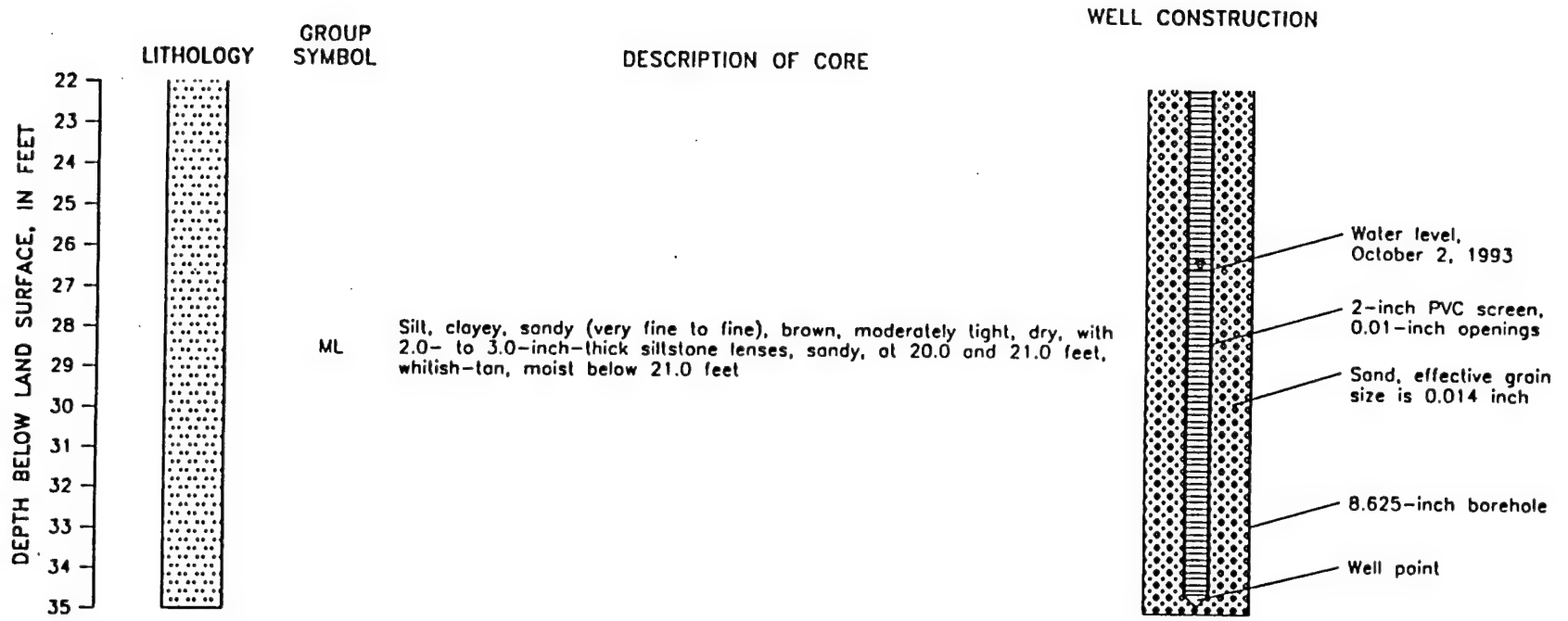
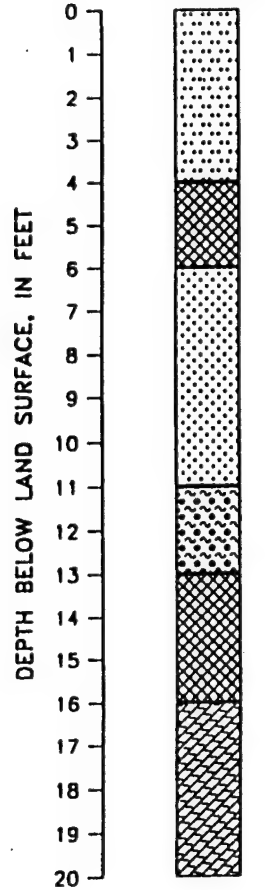
WELL 198--Continued



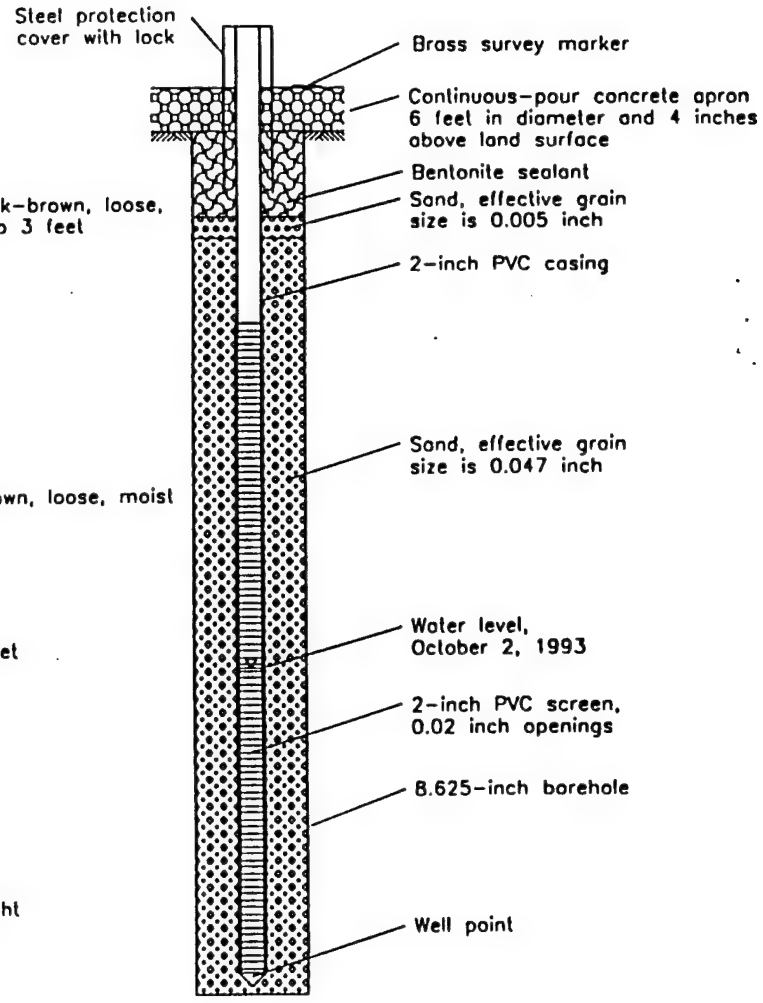
WELL 199

LAND SURFACE ELEVATION 6,085.45 FEET ABOVE SEA LEVEL



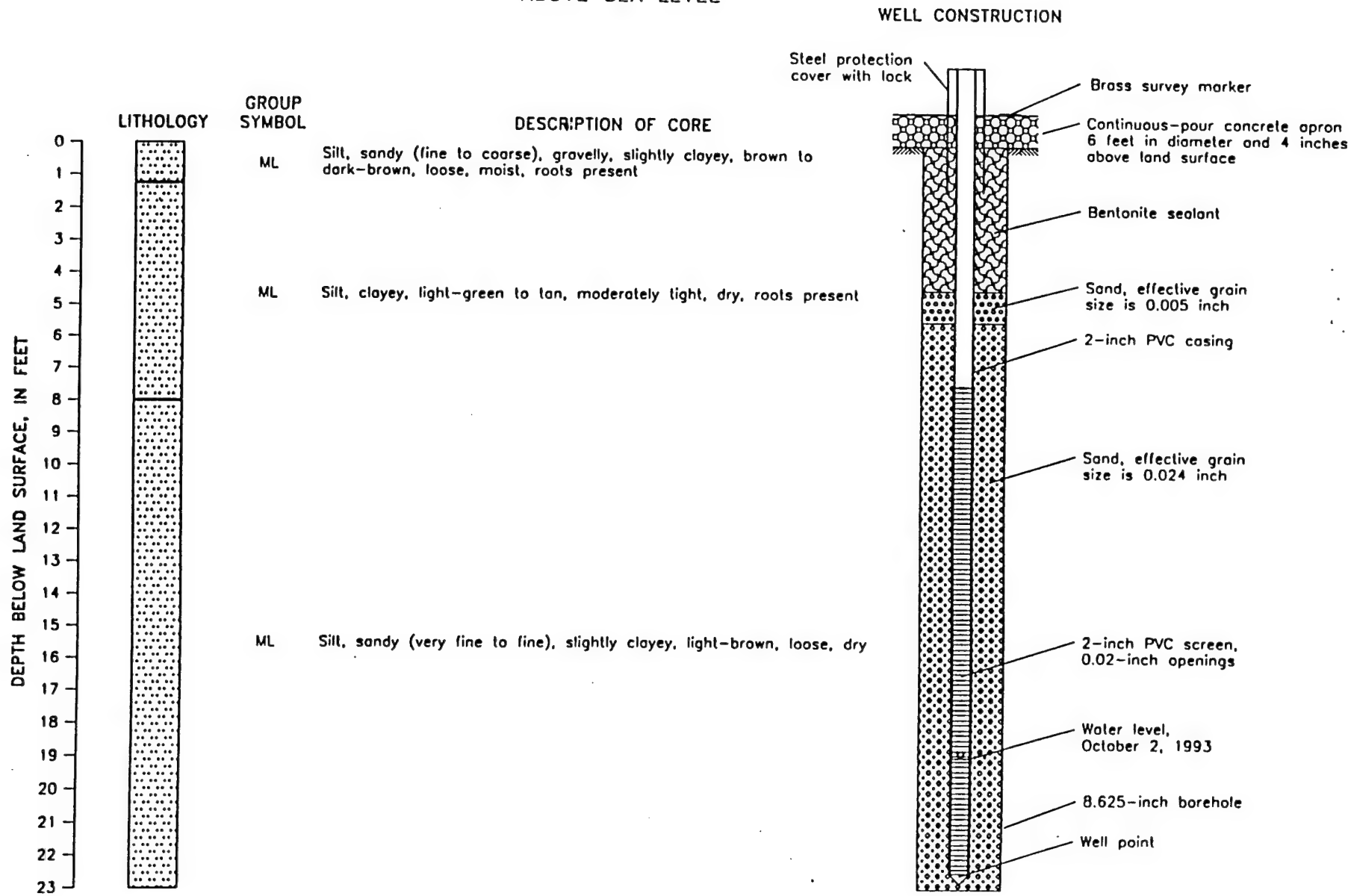
LITHOLOGY	GROUP SYMBOL	DESCRIPTION OF CORE
	ML	Silt, sandy (very fine to fine), clayey, light-brown to dark-brown, loose, top foot is moist, dry from 2.0 to 3.0 feet, roots in top 3 feet
	NA	Lost core
	SP	Sand, very coarse to coarse, gravelly, slightly clayey, brown, loose, moist
	SC	Sand, medium to coarse, slightly clayey, brown, loose, wet
	NA	Lost core
	SCSM	Sand, very fine to medium, clayey, silty, gray-brown, tight

WELL CONSTRUCTION



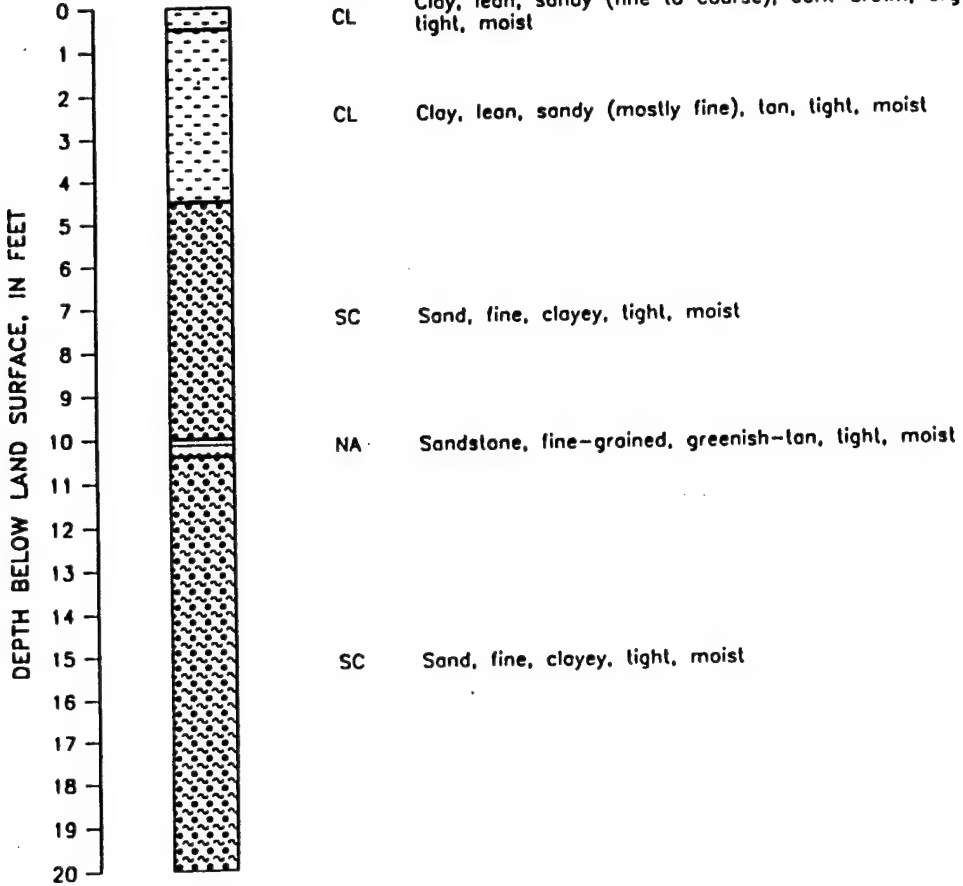
WELL 200

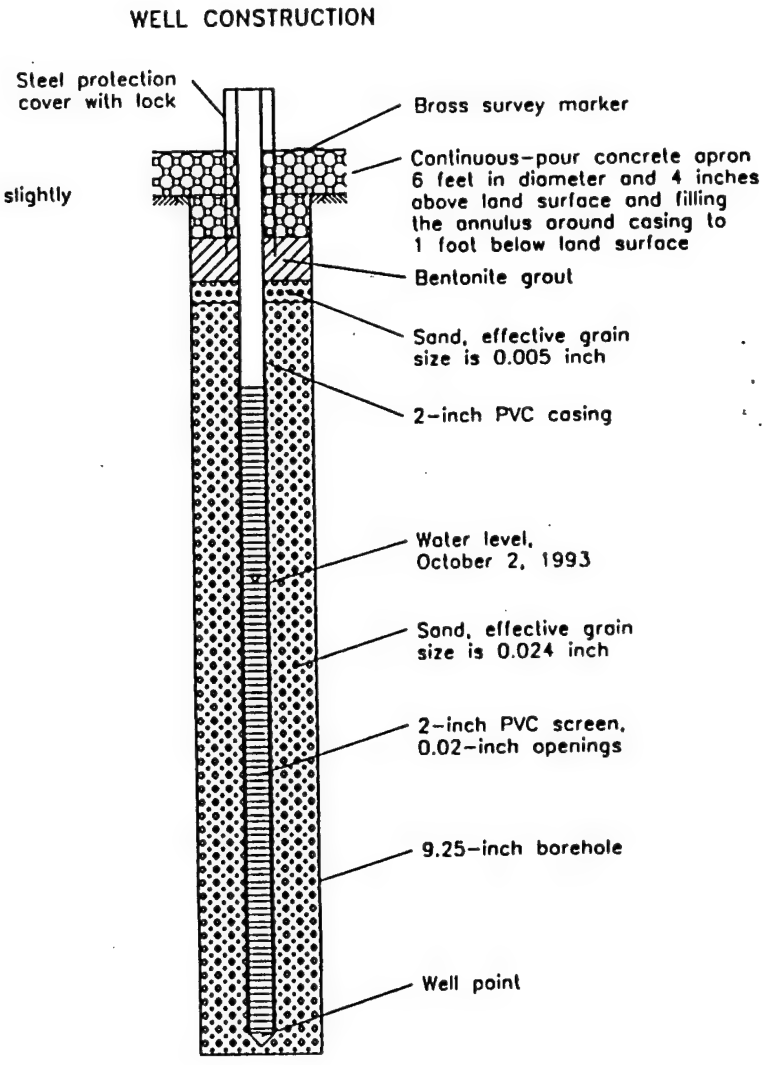
LAND SURFACE ELEVATION 6,107.07 FEET ABOVE SEA LEVEL



WELL 201

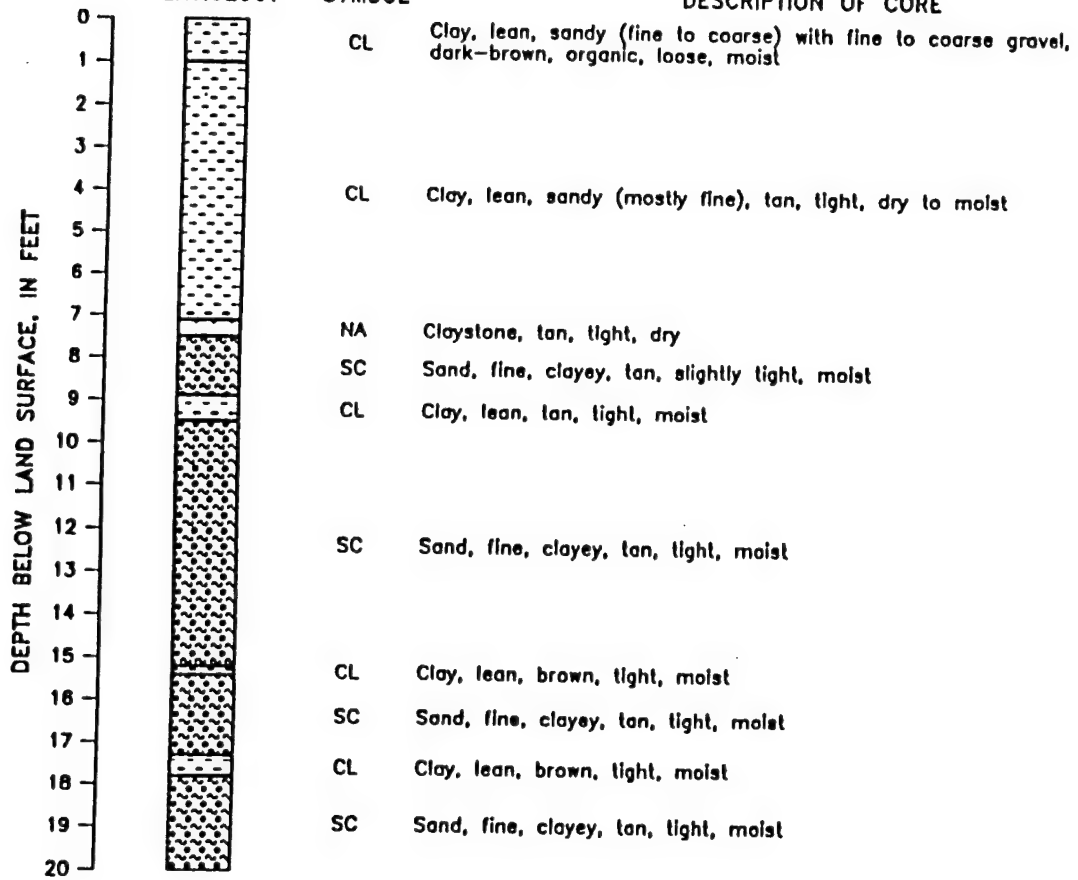
LAND SURFACE ELEVATION 6,110.79 FEET ABOVE SEA LEVEL





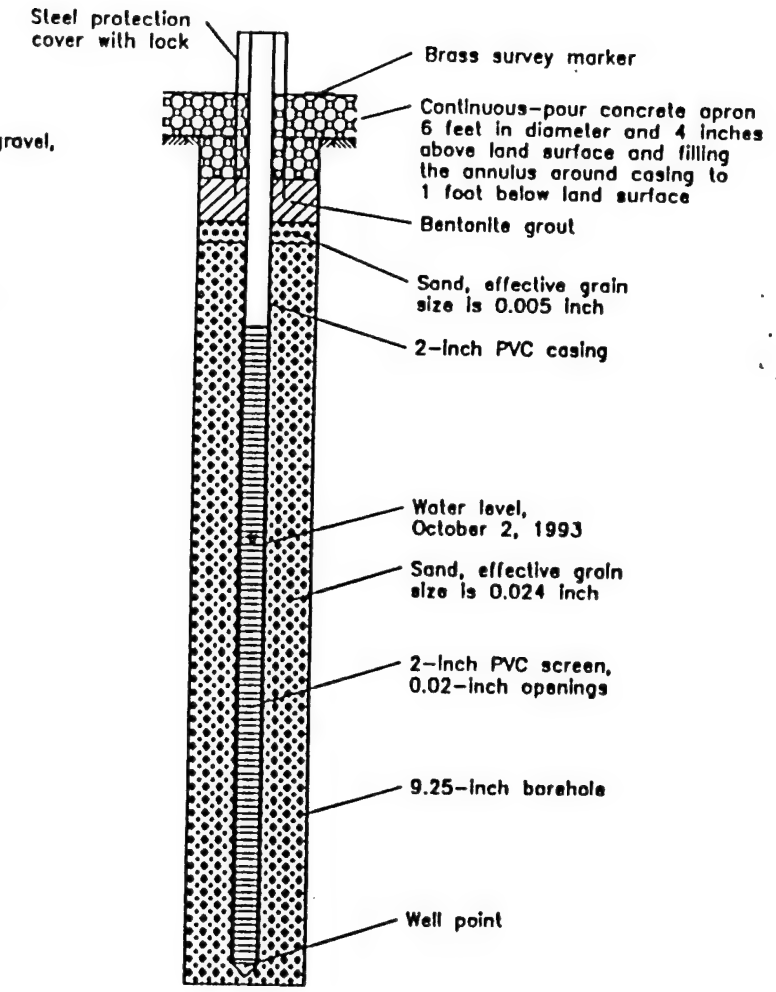
WELL 203

LAND SURFACE ELEVATION 6,117.11 FEET ABOVE SEA LEVEL



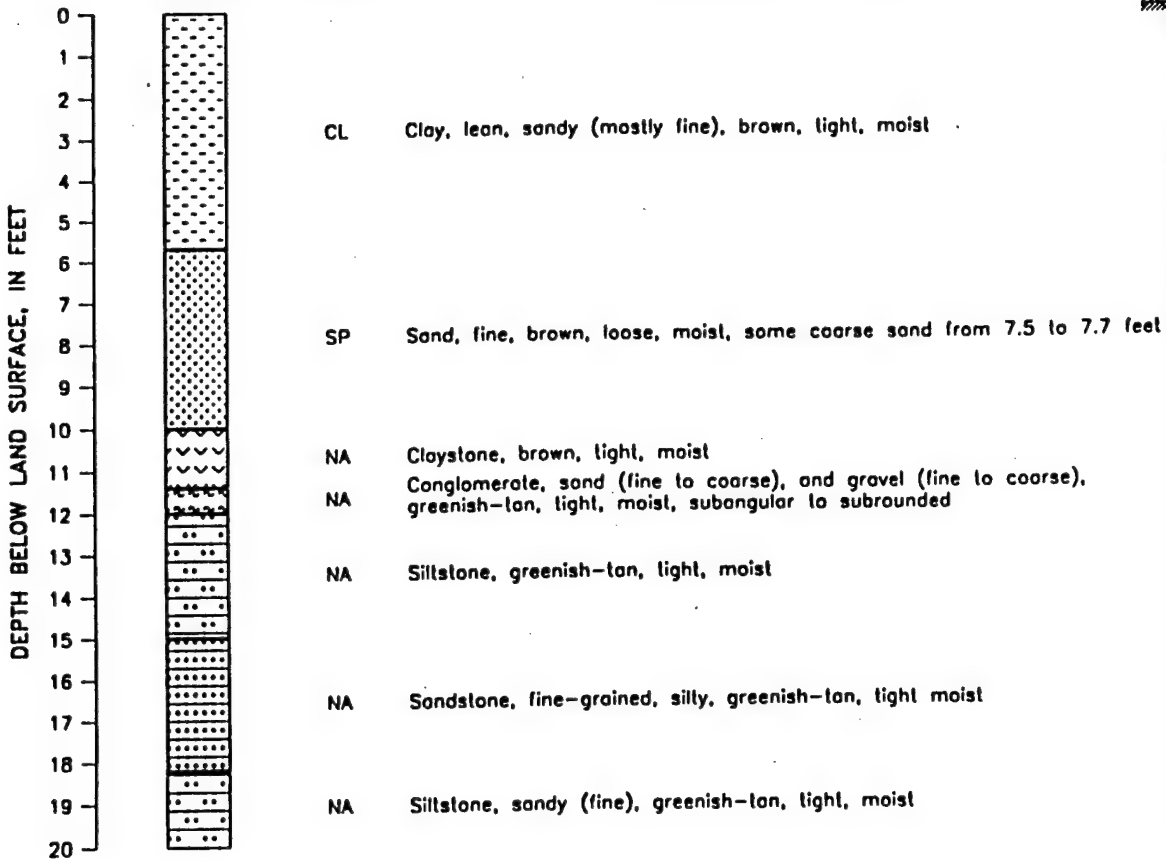
LITHOLOGY	GROUP SYMBOL	DESCRIPTION OF CORE
	CL	Clay, lean, sandy (fine to coarse) with fine to coarse gravel, dark-brown, organic, loose, moist
	CL	Clay, lean, sandy (mostly fine), tan, tight, dry to moist
	NA	Claystone, tan, tight, dry
	SC	Sand, fine, clayey, tan, slightly tight, moist
	CL	Clay, lean, tan, tight, moist
	SC	Sand, fine, clayey, tan, tight, moist
	CL	Clay, lean, brown, tight, moist
	SC	Sand, fine, clayey, tan, tight, moist
	CL	Clay, lean, brown, tight, moist
	SC	Sand, fine, clayey, tan, tight, moist

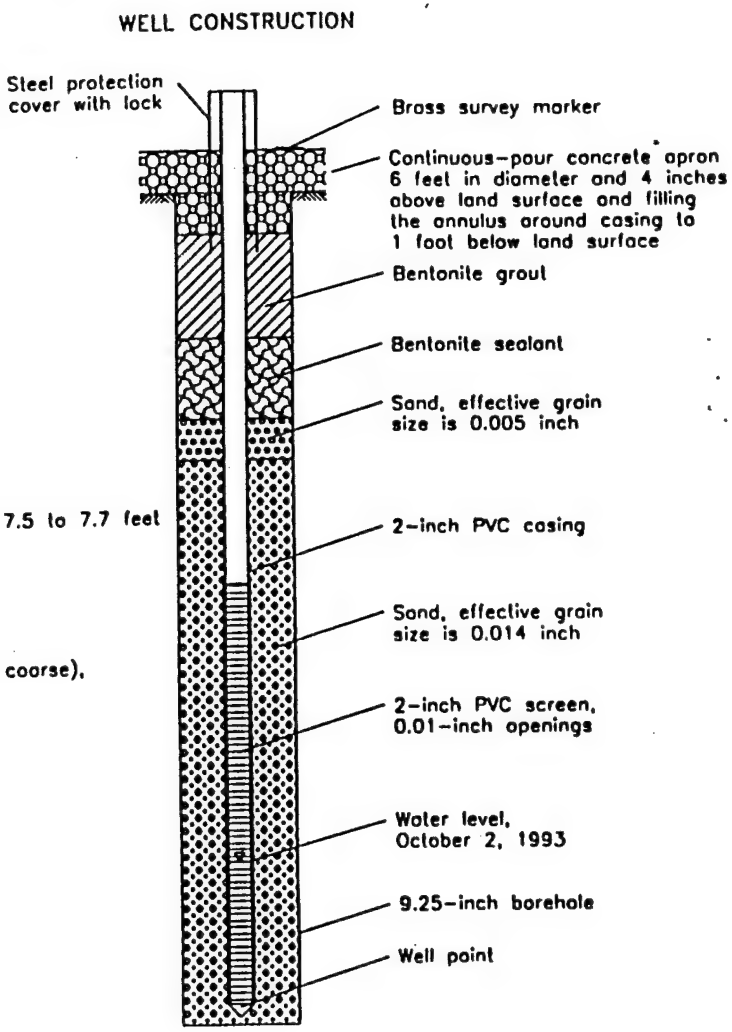
WELL CONSTRUCTION



WELL 205

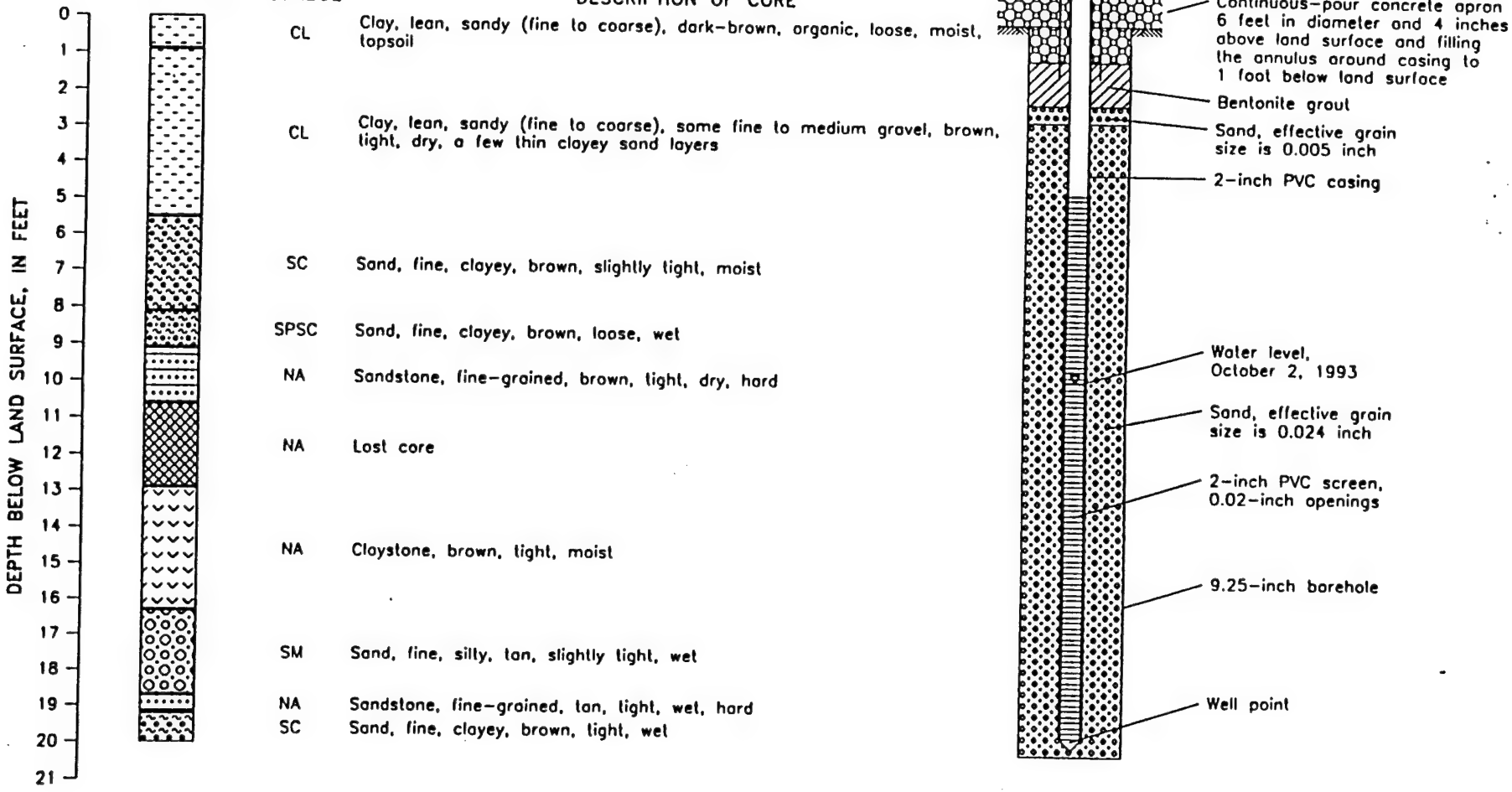
LAND SURFACE ELEVATION 6,129.03 FEET ABOVE SEA LEVEL





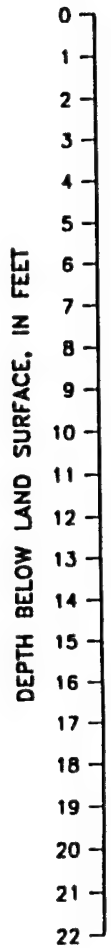
WELL 206

LAND SURFACE ELEVATION 6,124.12 FEET
ABOVE SEA LEVEL



WELL 207

LAND SURFACE ELEVATION 6,136.98 FEET ABOVE SEA LEVEL



LITHOLOGY	GROUP SYMBOL	DESCRIPTION OF CORE
	CL	Clay, lean, sandy (fine to coarse), dark-brown, organic, loose, moist
	CL	Clay, lean, sandy (fine to medium), brown, light, moist
	SC	Sand, mostly fine to medium, clayey, brown, light, dry
	CL	Clay, lean, sandy (fine), brown, light, dry
	CL	Clay, lean, brown, light, moist
	CL	Clay, lean, and claystone, brown, light, moist
	SC	Sand, fine, clayey, brown, light, moist
	CL	Clay, lean, sandy (fine), with claystone, brown, light, moist, thin clayey sand lenses
	SP	Sand, fine to medium, brown, loose, moist, bottom 0.2 feet cemented
	NA	Claystone, brown, light, moist

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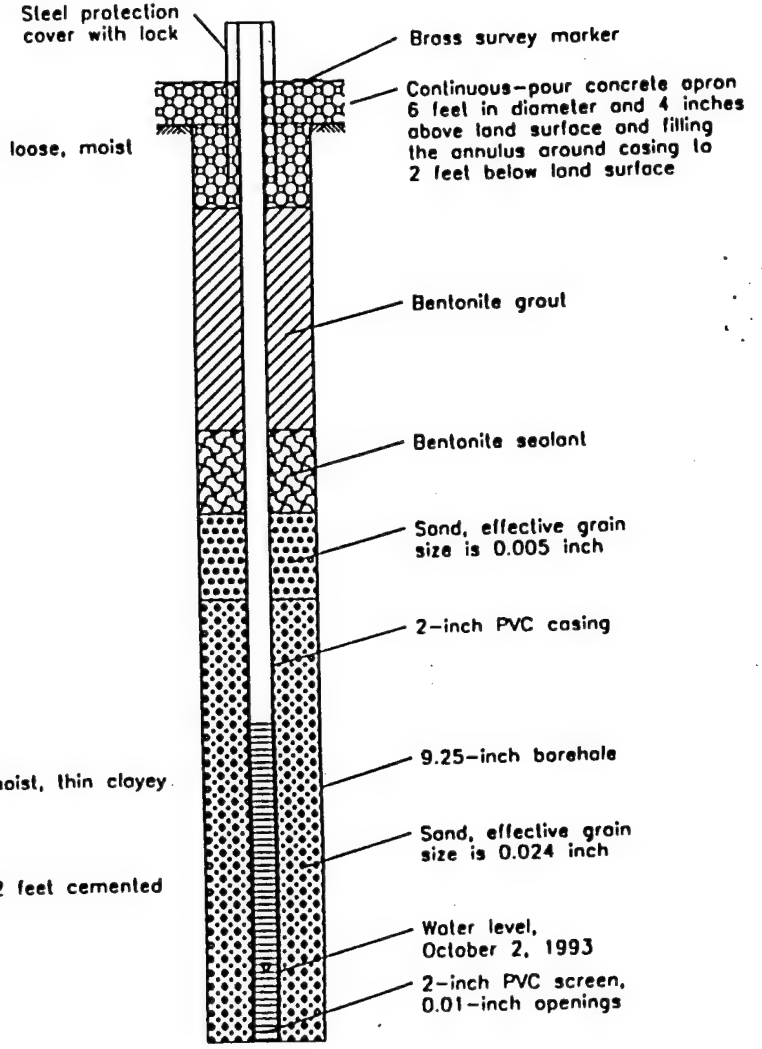
WELL CONSTRUCTION



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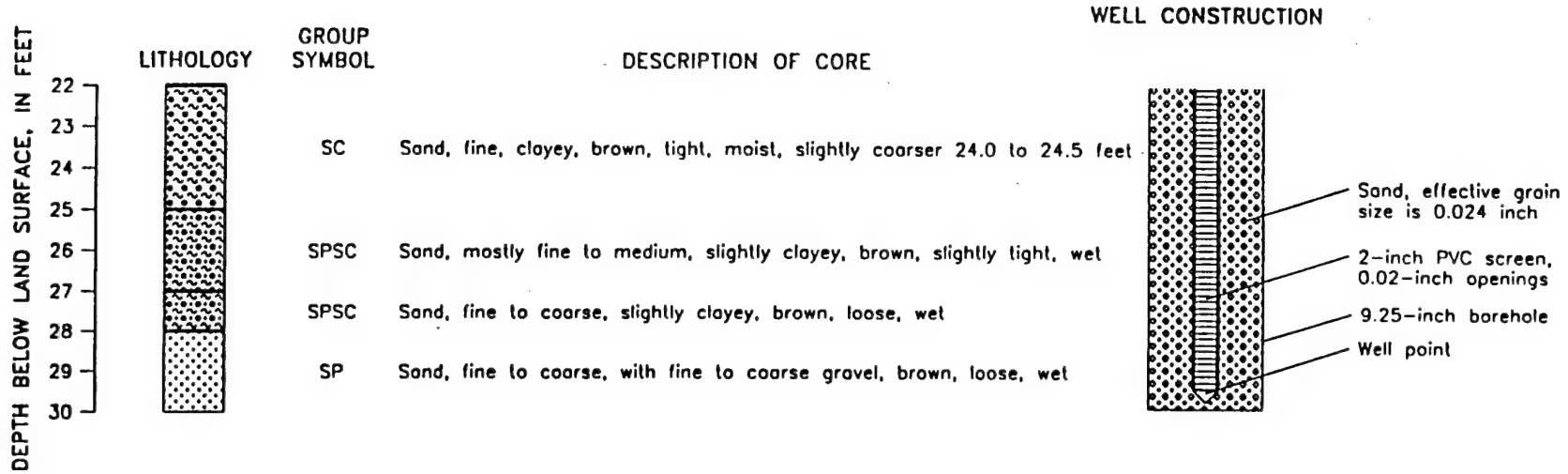
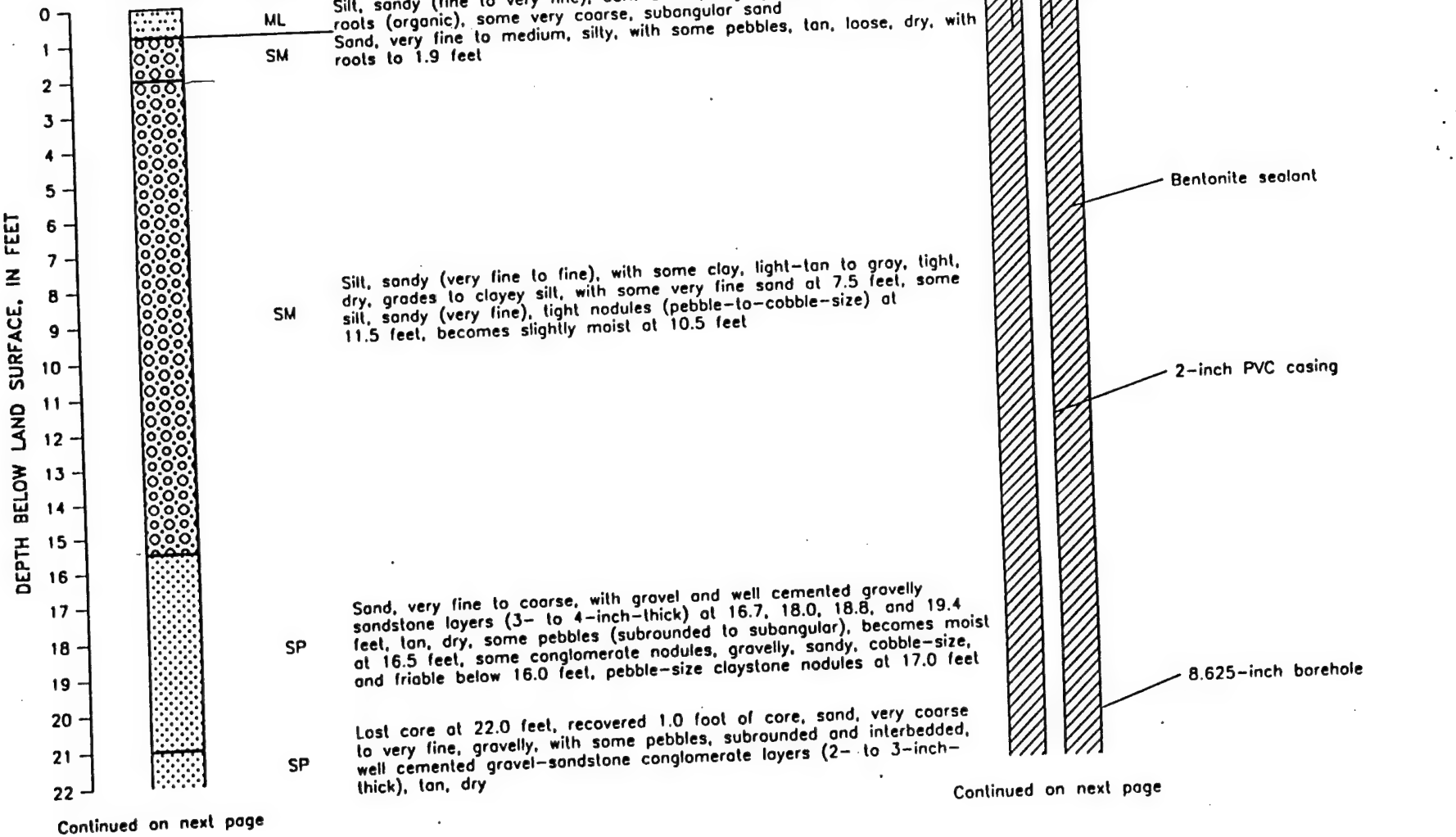
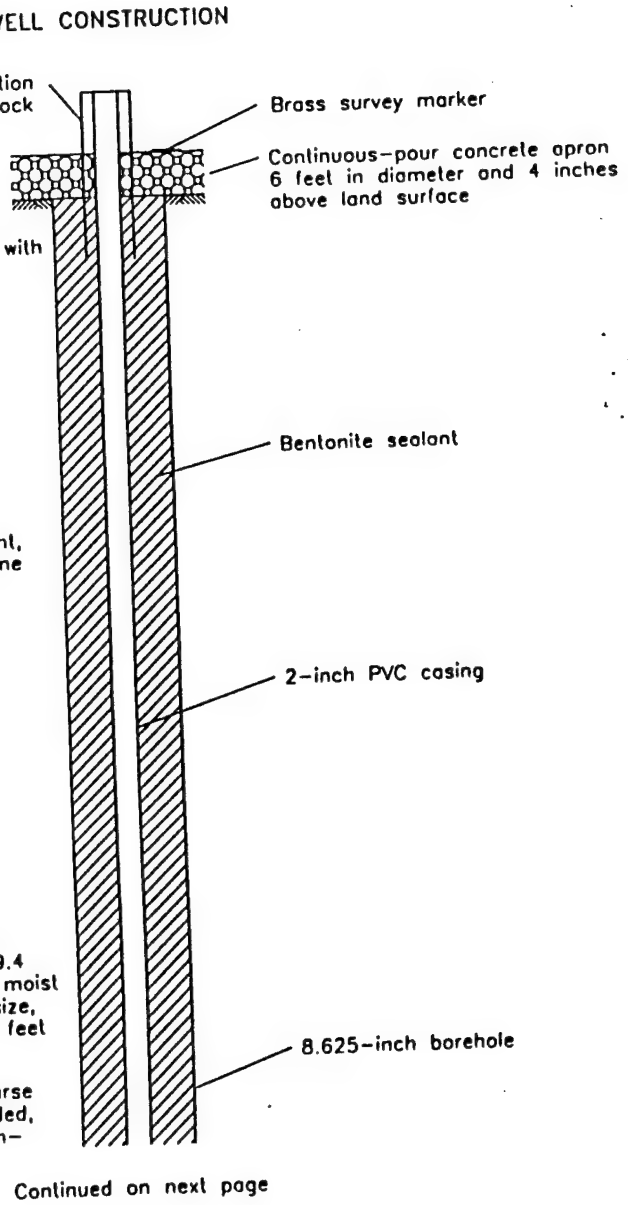
WELL 207--Continued



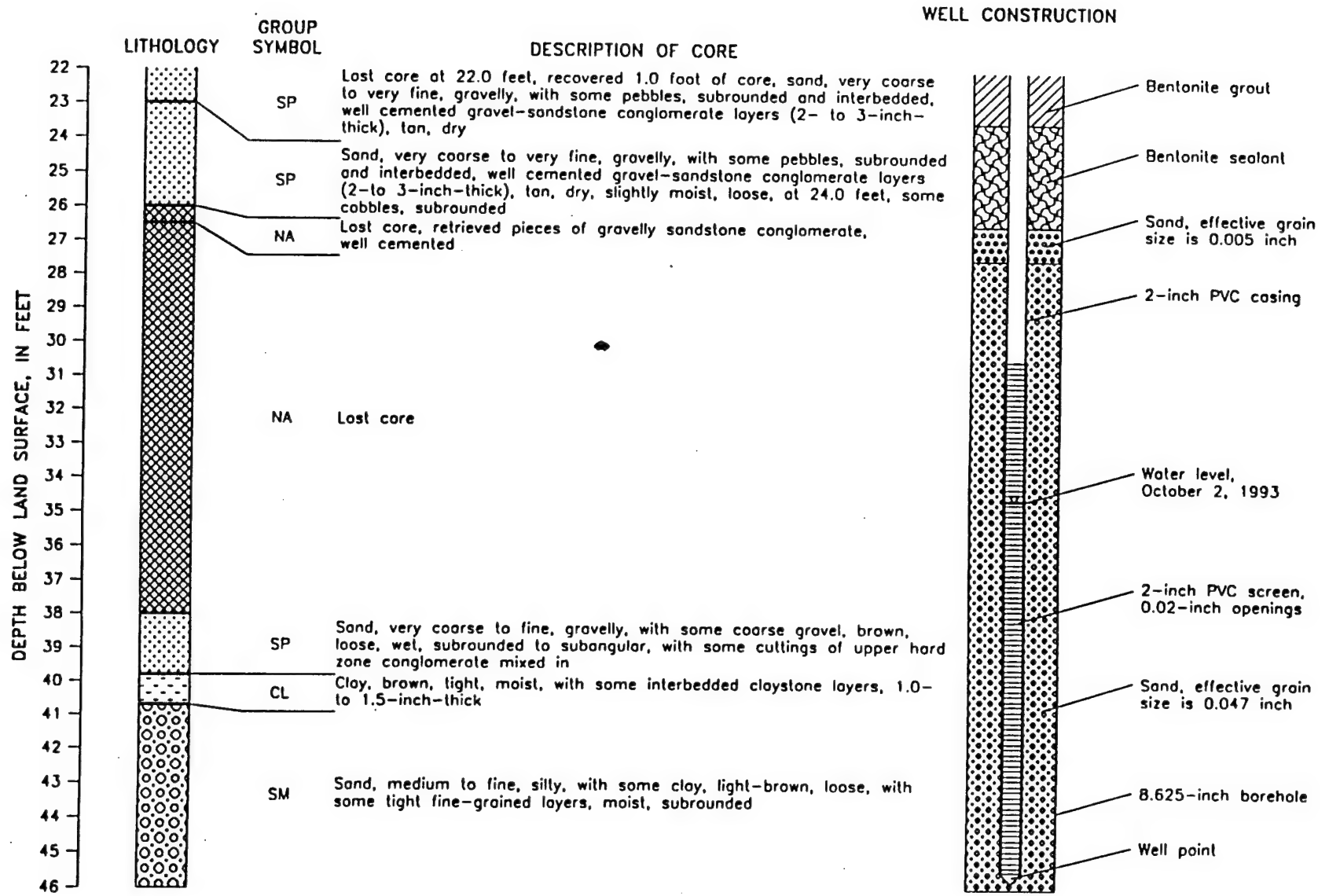
WELL 208

LAND SURFACE ELEVATION 6,151.79 FEET ABOVE SEA LEVEL



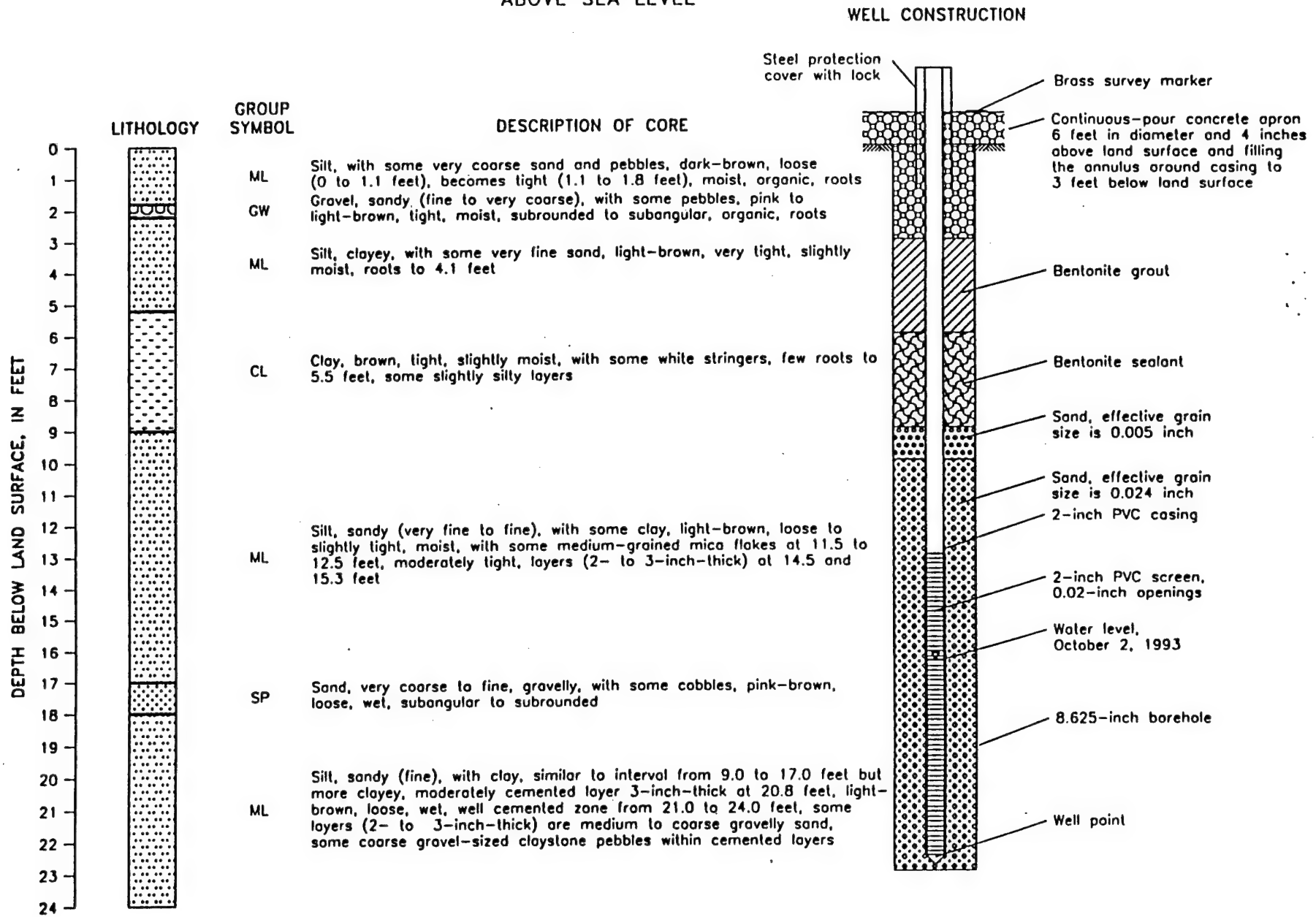


WELL 208--Continued



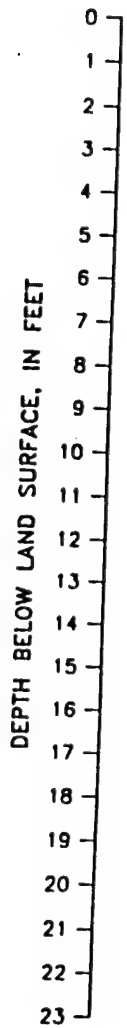
WELL 209

LAND SURFACE ELEVATION 6,132.21 FEET ABOVE SEA LEVEL



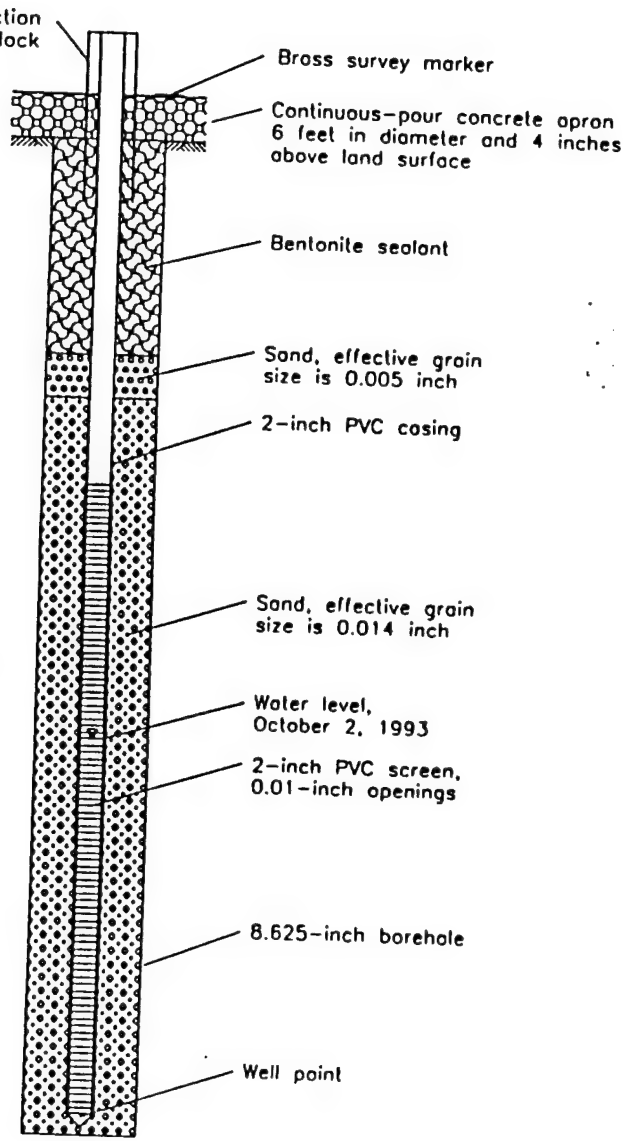
WELL 210

LAND SURFACE ELEVATION 6,125.78 FEET ABOVE SEA LEVEL



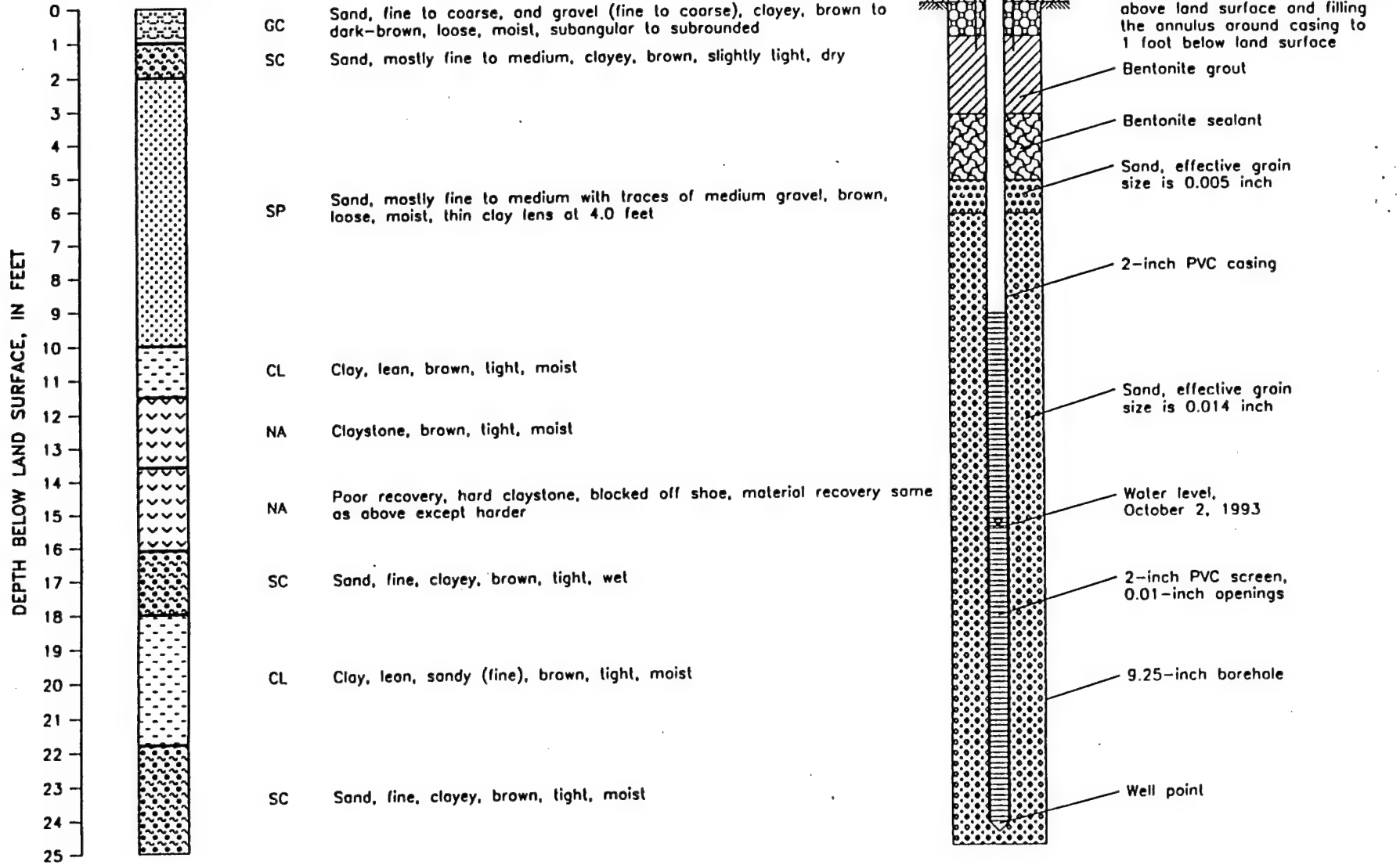
GROUP SYMBOL	DESCRIPTION OF CORE
ML	Silt, sandy (fine to medium), with some gravel, dark-brown, slightly tight, moist, gravel is subangular to subrounded, organic, roots
SM	Sand, fine to medium, silty, with some gravel, light-brown, slightly tight, dry, roots
ML	Silt, clayey, light-brown, loose, moist, roots end at 5.2 feet
NA	Lost core
ML	Silt, clayey, light-brown, loose, moist, with 4-inch-thick well cemented siltstone layers at 8.5, 13.0 and 15.7 feet, very hard, well cemented, sandy (medium to coarse), siltstone layer (6-inch-thick) at 16.0 to 16.5 feet, moderately cemented siltstone with pebble-size claystone chips at 17.2 feet (3-inch-thick)
ML	Silt, sandy (very fine), with some clay, light-brown to tan, loose, wet

WELL CONSTRUCTION

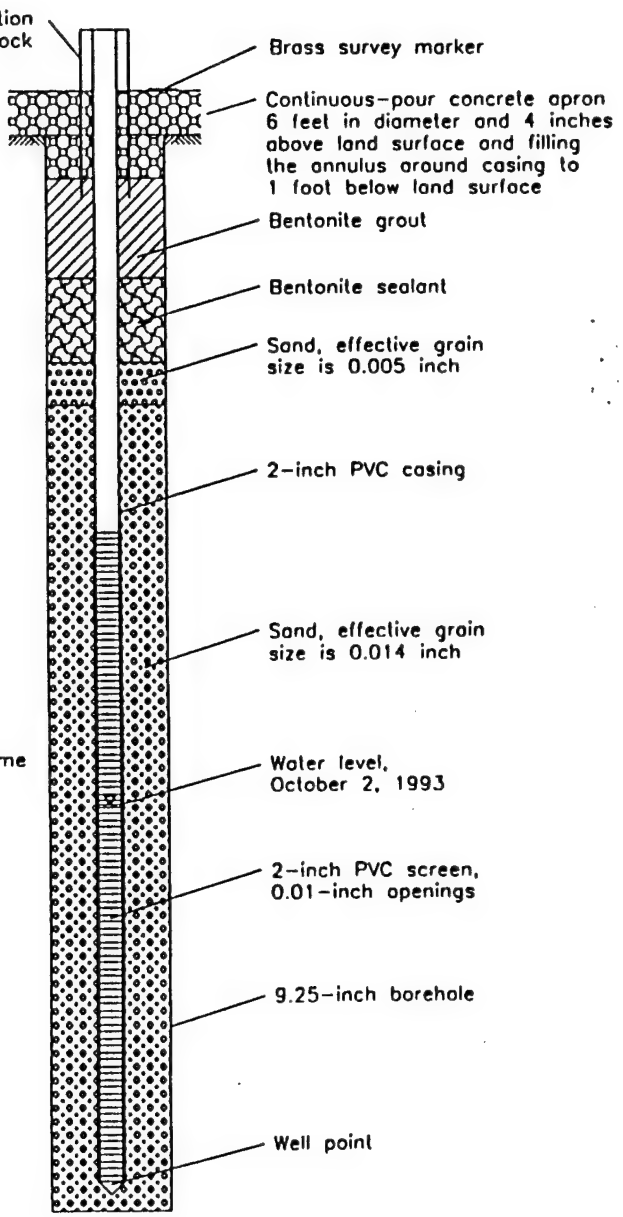


WELL 211

LAND SURFACE ELEVATION 6,122.87 FEET ABOVE SEA LEVEL

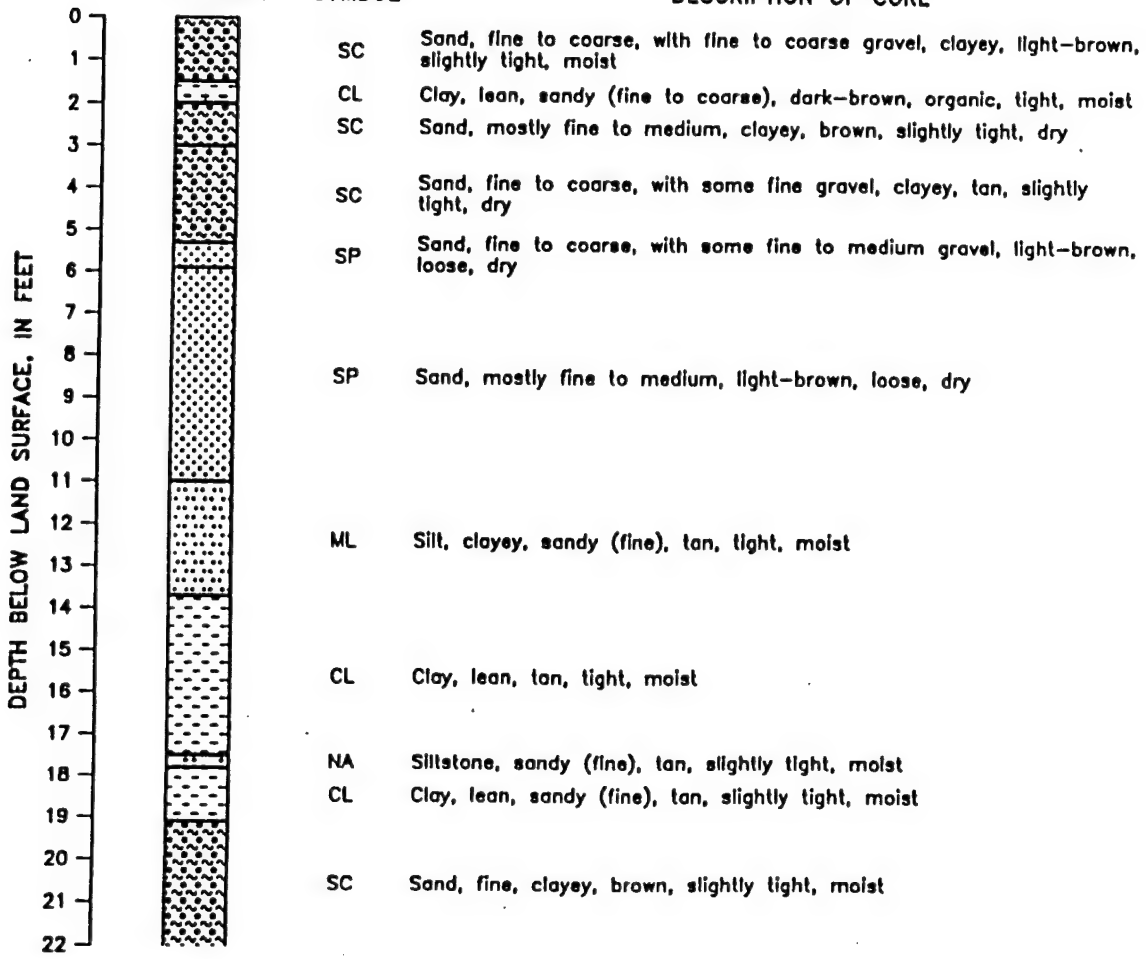


WELL CONSTRUCTION



WELL 229

LAND SURFACE ELEVATION 6,166.41 FEET ABOVE SEA LEVEL



GROUP SYMBOL	DESCRIPTION OF CORE
SC	Sand, fine to coarse, with fine to coarse gravel, clayey, light-brown, slightly tight, moist
CL	Clay, lean, sandy (fine to coarse), dark-brown, organic, tight, moist
SC	Sand, mostly fine to medium, clayey, brown, slightly tight, dry
SC	Sand, fine to coarse, with some fine gravel, clayey, tan, slightly tight, dry
SP	Sand, fine to coarse, with some fine to medium gravel, light-brown, loose, dry
SP	Sand, mostly fine to medium, light-brown, loose, dry
ML	Silt, clayey, sandy (fine), tan, tight, moist
CL	Clay, lean, tan, tight, moist
NA	Siltstone, sandy (fine), tan, slightly tight, moist
CL	Clay, lean, sandy (fine), tan, slightly tight, moist
SC	Sand, fine, clayey, brown, slightly tight, moist

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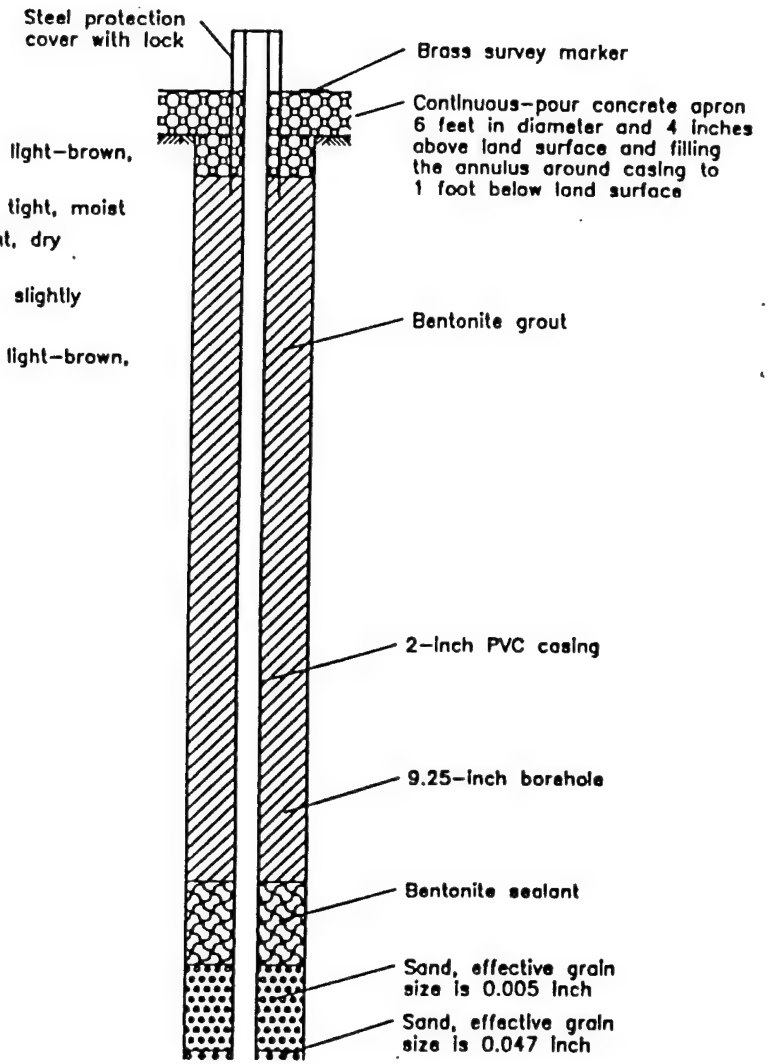
WELL CONSTRUCTION



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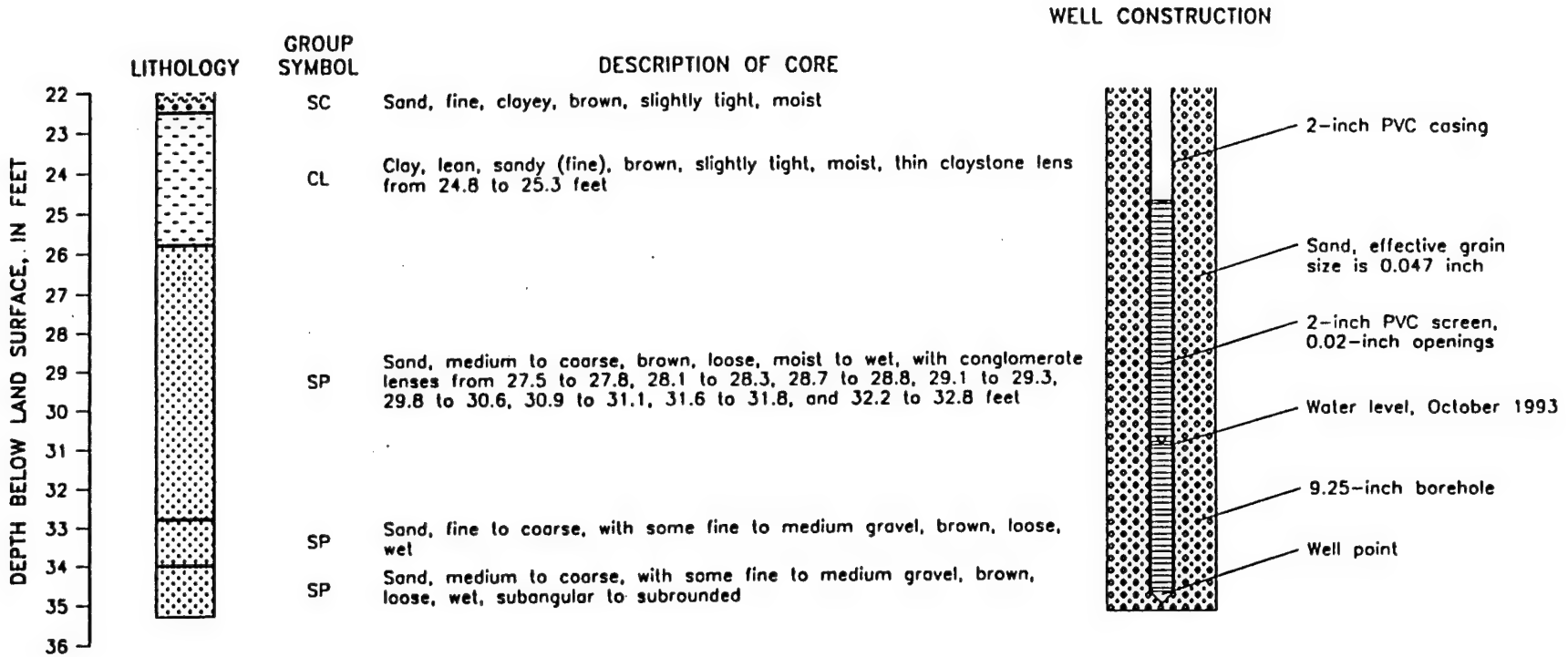
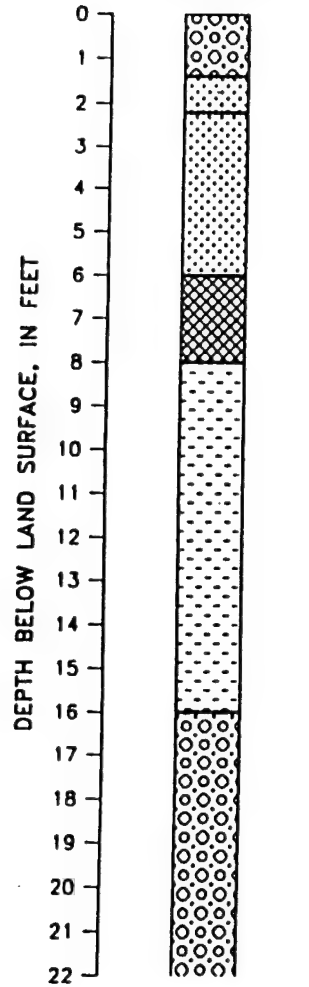
WELL 229--Continued



WELL 230

LAND SURFACE ELEVATION 6,161.62 FEET ABOVE SEA LEVEL



GROUP SYMBOL	DESCRIPTION OF CORE
SM	Sand, very fine to very coarse, silty, with gravel, rusty-dark-brown, loose, moist, subrounded to subangular, roots
SP	Sand, fine to very coarse, light-brown, loose, moist
SW	Sand, medium to very coarse, gravelly, light-brown to pink, loose, moist, angular to subrounded, some cobbles
NA	Lost core
CL	Clay, silty, dark-brown, slightly tight, moist, some tight clay nodules, (pebble-size) at 12.5 feet
SM	Sand, fine to medium, silty, with some clay, dark-brown, slightly tight, moist, and moderately tight clay layer 22.5 to 23.0 feet, grades to fine to coarse sand at 25.0 feet, with some pebble-size granite stones and claystone

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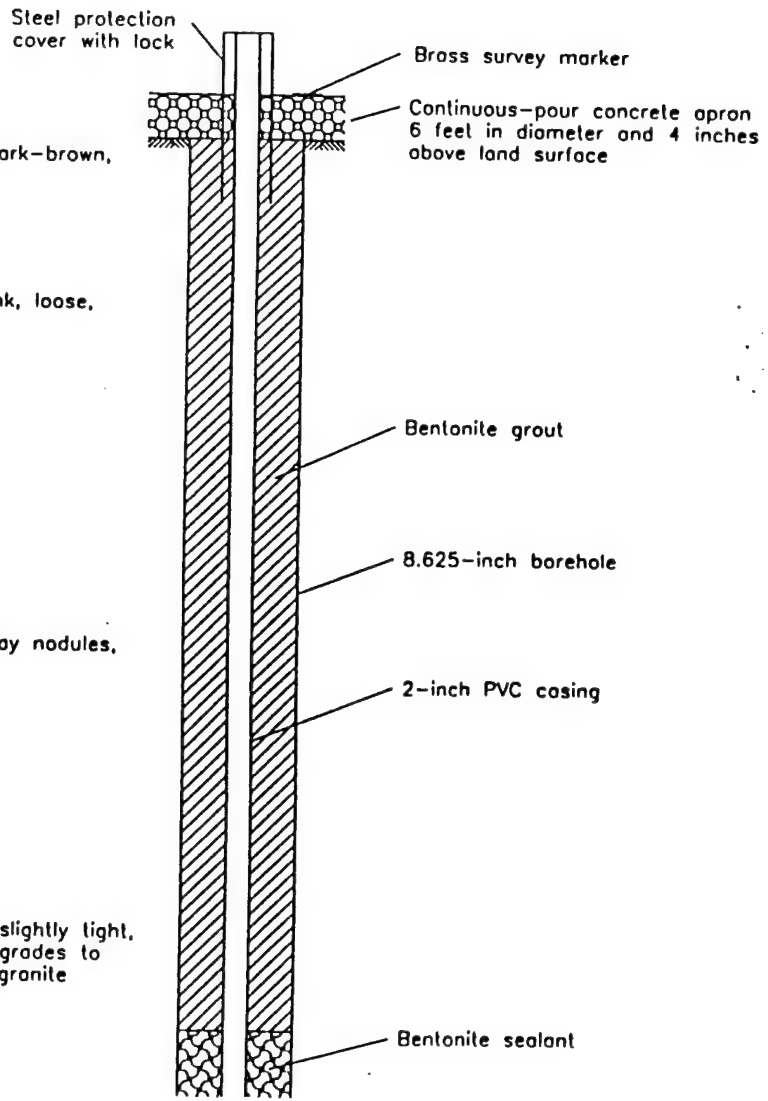
WELL CONSTRUCTION



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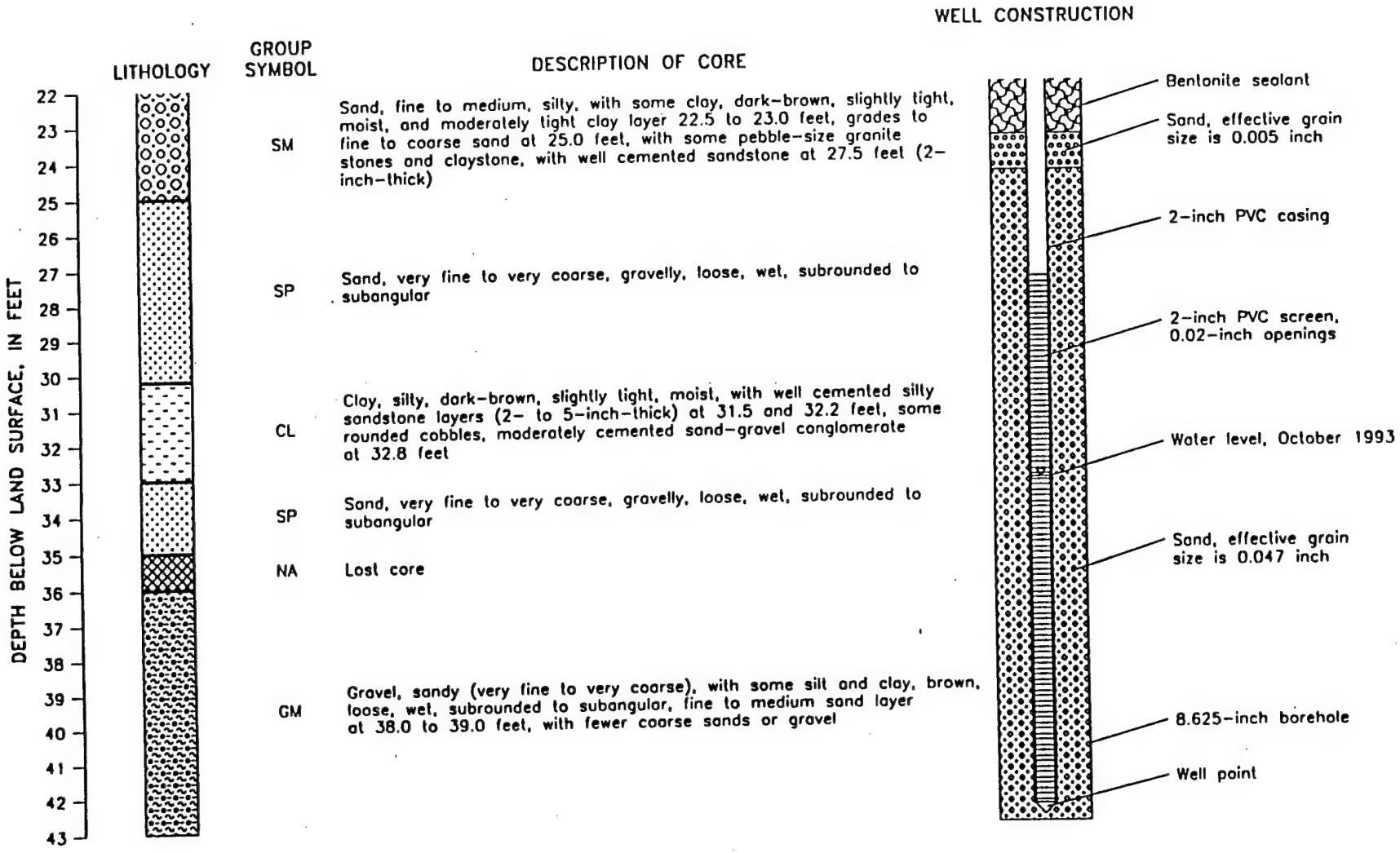
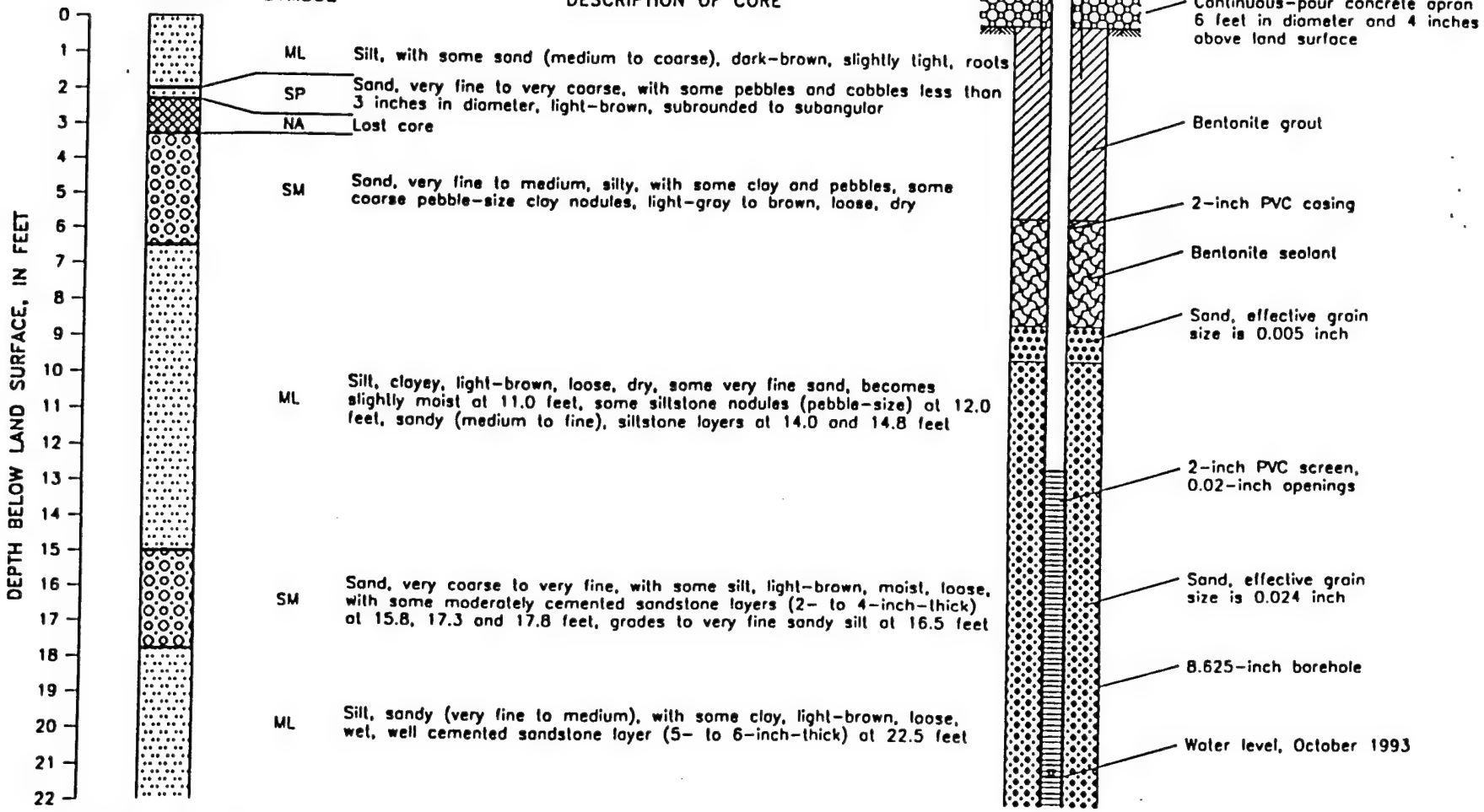
WELL 230--Continued



WELL 231

LAND SURFACE ELEVATION 6,124.66 FEET ABOVE SEA LEVEL



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WELL CONSTRUCTION

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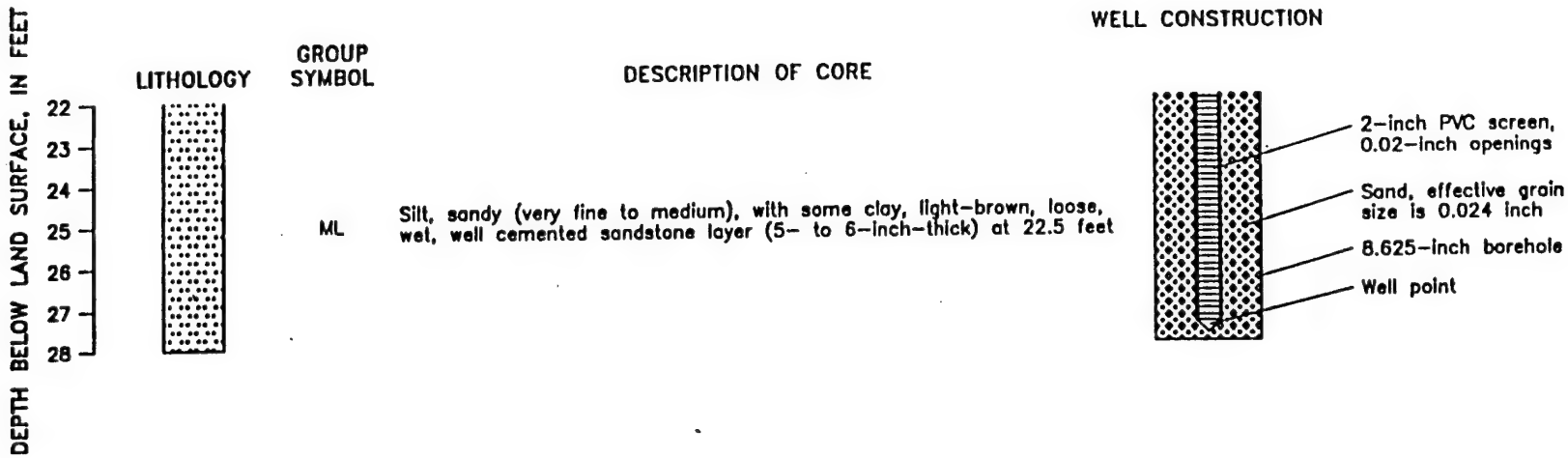
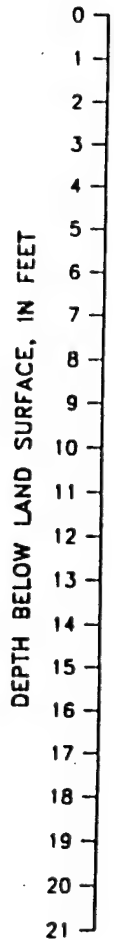
WELL 231--Continued



WELL 232

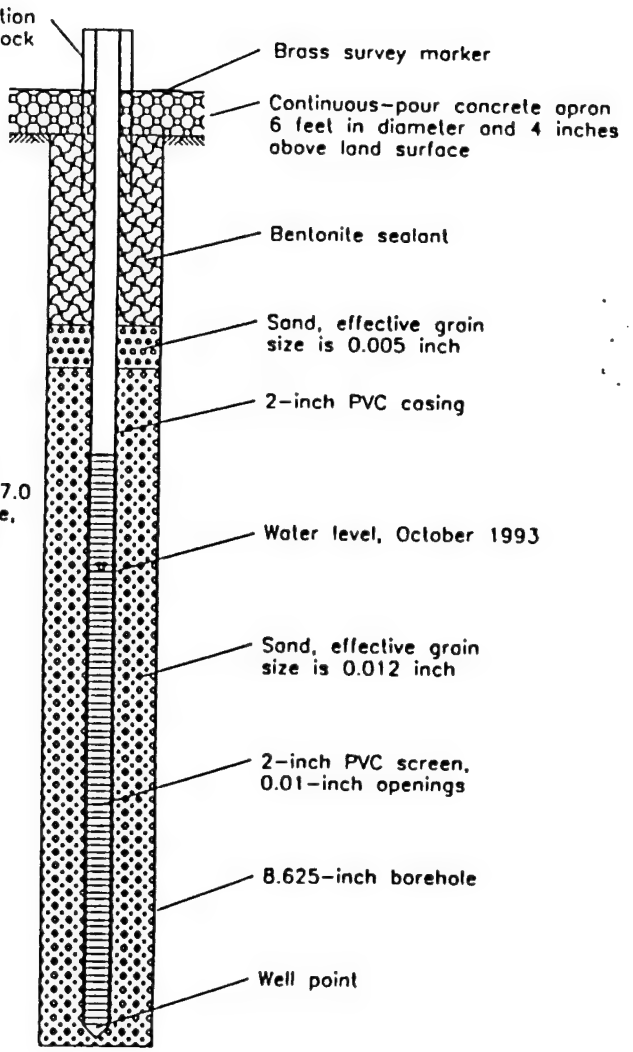
LAND SURFACE ELEVATION 6,088.94 FEET ABOVE SEA LEVEL



LITHOLOGY

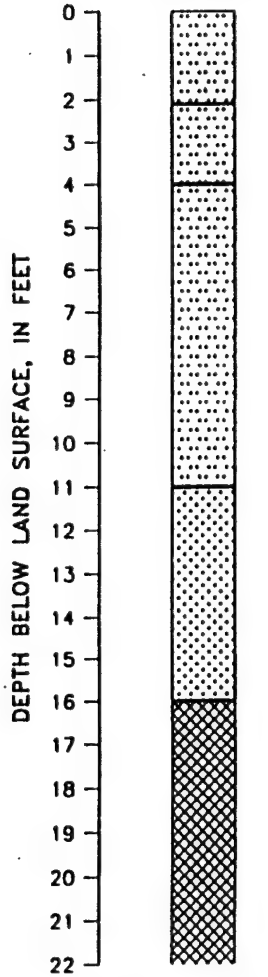
GROUP SYMBOL	DESCRIPTION OF CORE
ML	Silt, sandy (coarse to very coarse), with some gravel, dark-brown, loose, moist, sand and gravel is subrounded to subangular, roots to 1.8 feet
SM	Sand, very fine to fine, silty, tan to light-brown, loose, slightly moist, roots to 3.0 feet, some clay, layer of very fine white sandy stringers (0.5- to 1.0-centimeter-thick) at 5.7 feet, becomes slightly tight at 7.0 feet, some medium sand at 9.2 to 10.5 feet, well cemented sandstone, fine- to medium-grained, layers at 12.5 and 15.2 feet about 5 to 6 inches thick
ML	Silt, clayey, with some very fine to medium sand, light-brown, slightly tight, moist, well cemented silty sandstone below 20.5 feet

WELL CONSTRUCTION



WELL 233

LAND SURFACE ELEVATION 6,157.69 FEET
ABOVE SEA LEVEL



GROUP SYMBOL	DESCRIPTION OF CORE
ML	Silt, sandy (fine), with gravel, dark-brown, slightly tight, slightly moist, roots
ML	Silt, sandy (very fine to fine), light-brown to tan, loose, dry, roots, some clay, grades to clayey silt below 4.0 feet
ML	Silt, clayey, light-brown to tan, loose, dry
SP	Sand, very fine to very coarse, gravelly, with some cobbles, well cemented gravelly sandstone conglomerate layer (2-inch-thick) at 12.4 feet, light-brown to pink, loose, dry, subrounded to subangular
NA	Lost core

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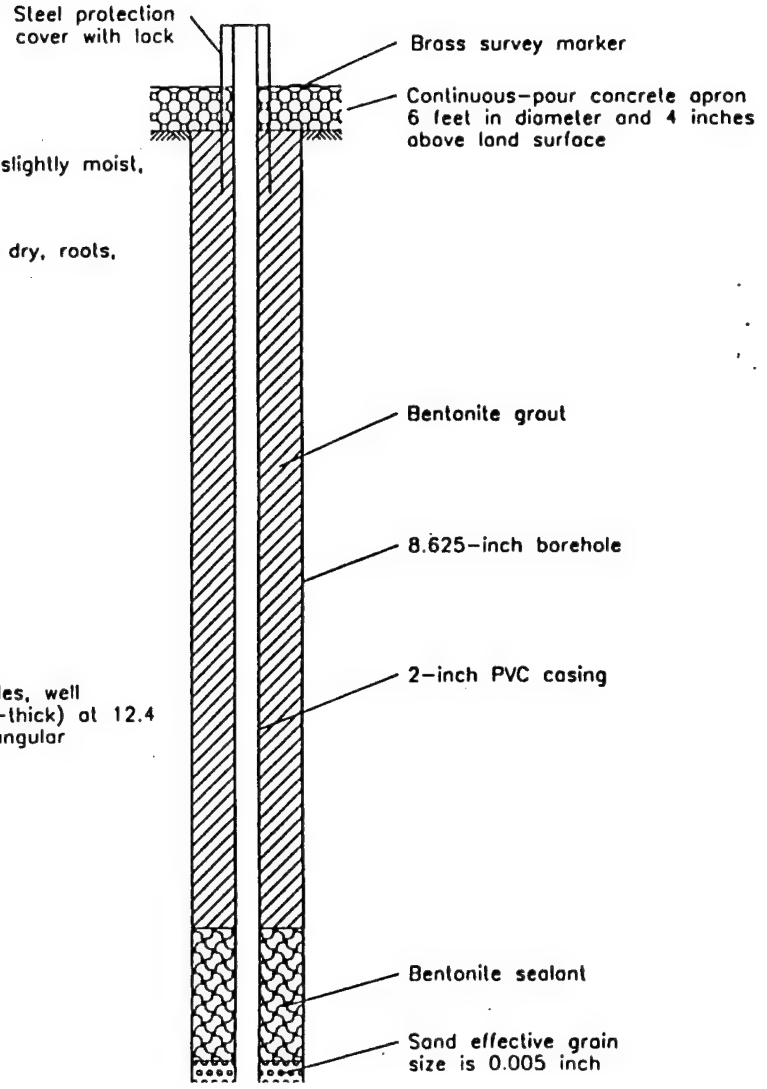
WELL CONSTRUCTION



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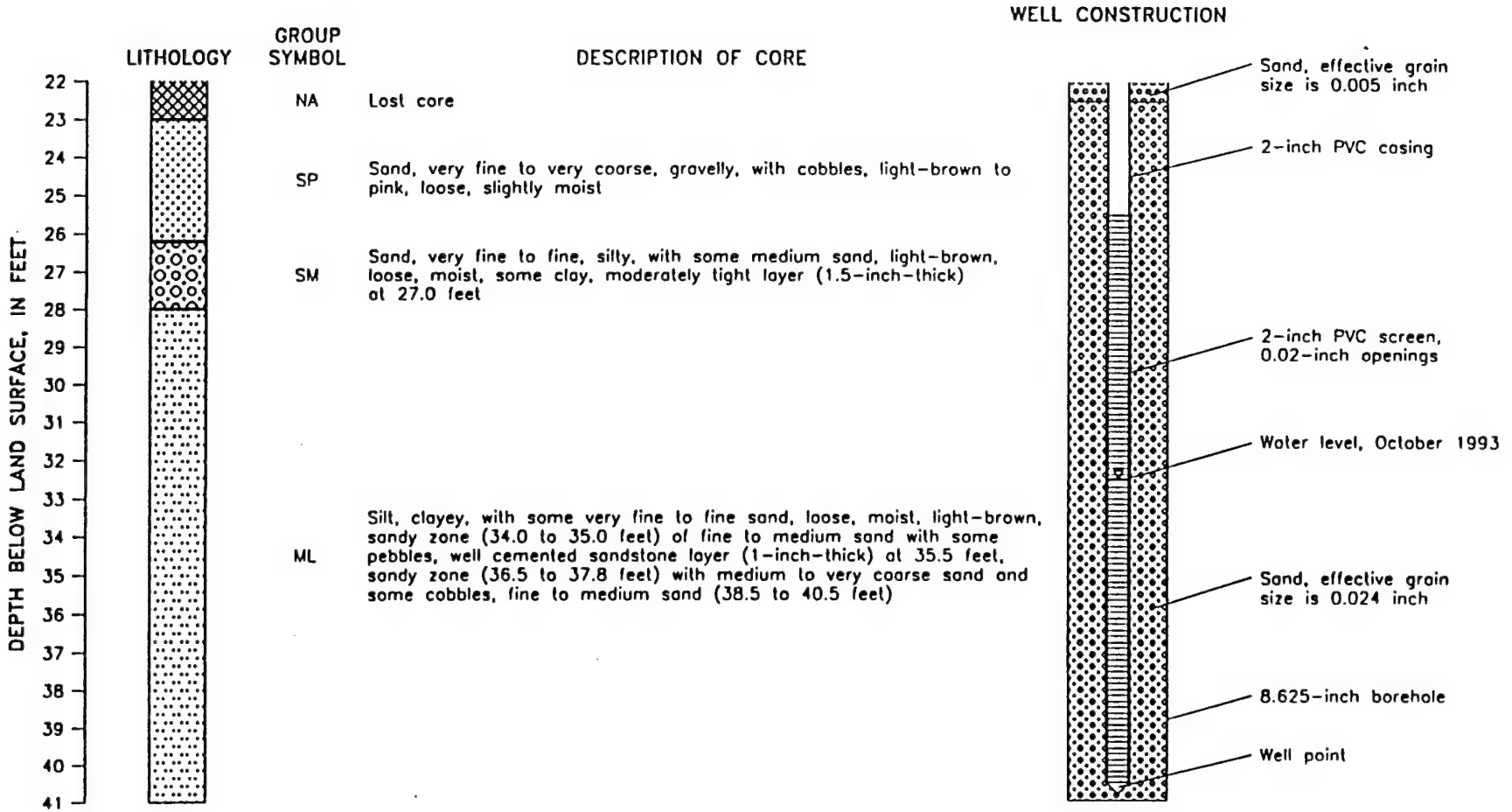
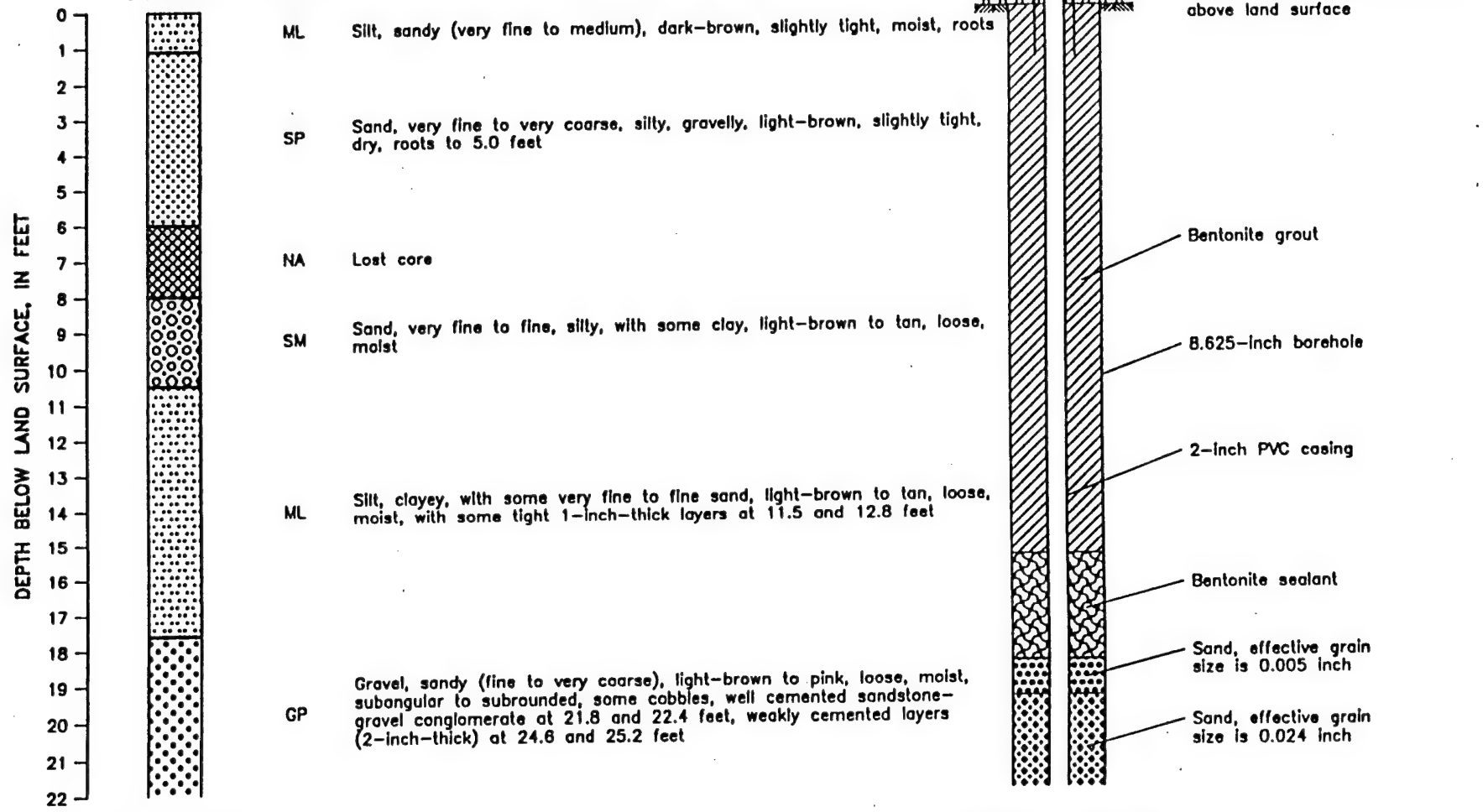
WELL 233--Continued



WELL 234

LAND SURFACE ELEVATION 6,164.68 FEET ABOVE SEA LEVEL



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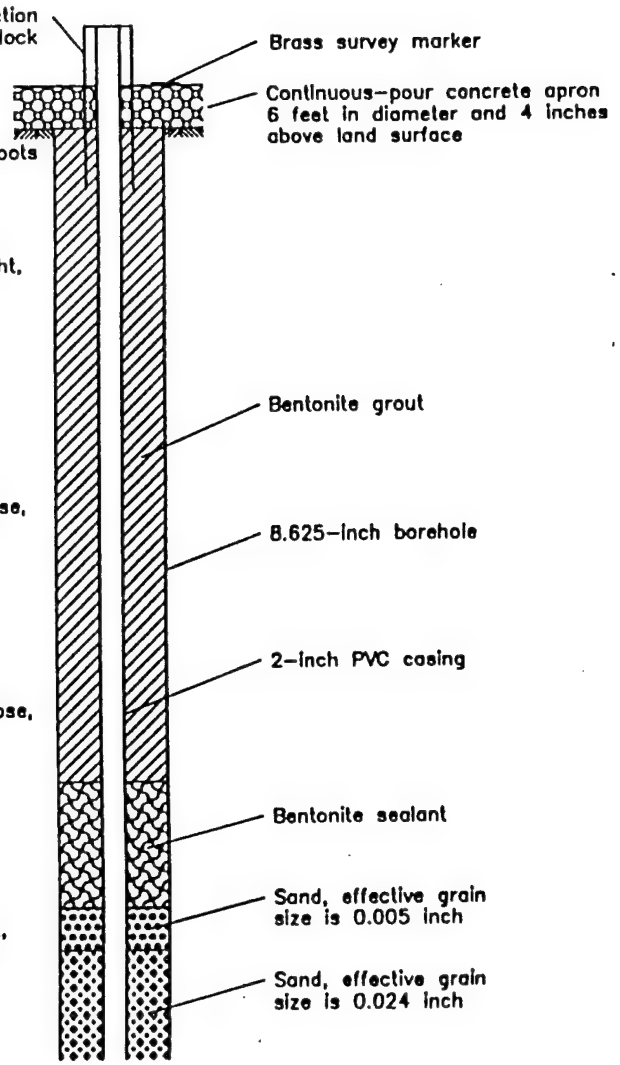
WELL CONSTRUCTION



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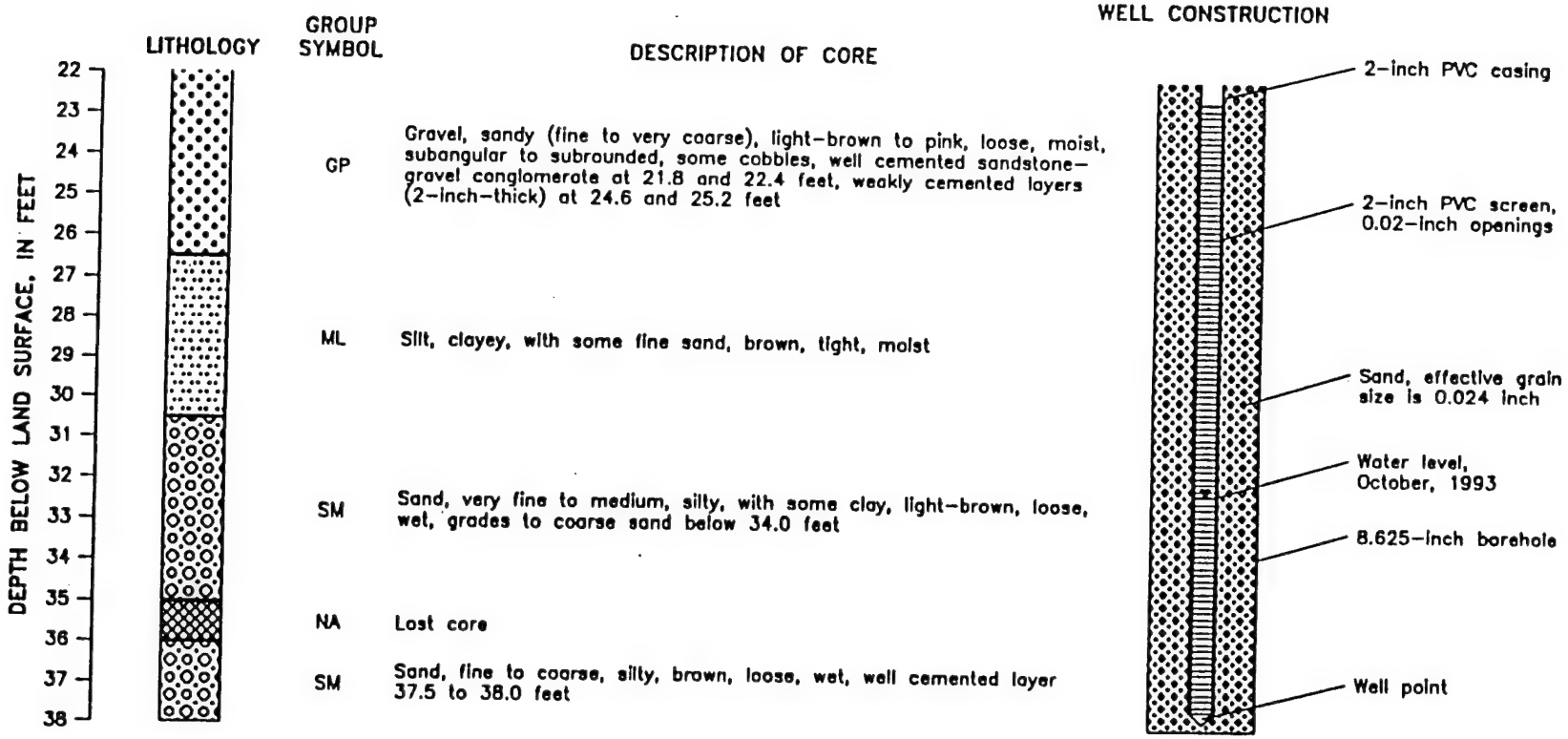
U/WL234-1.dwg PBC 10-19-1994

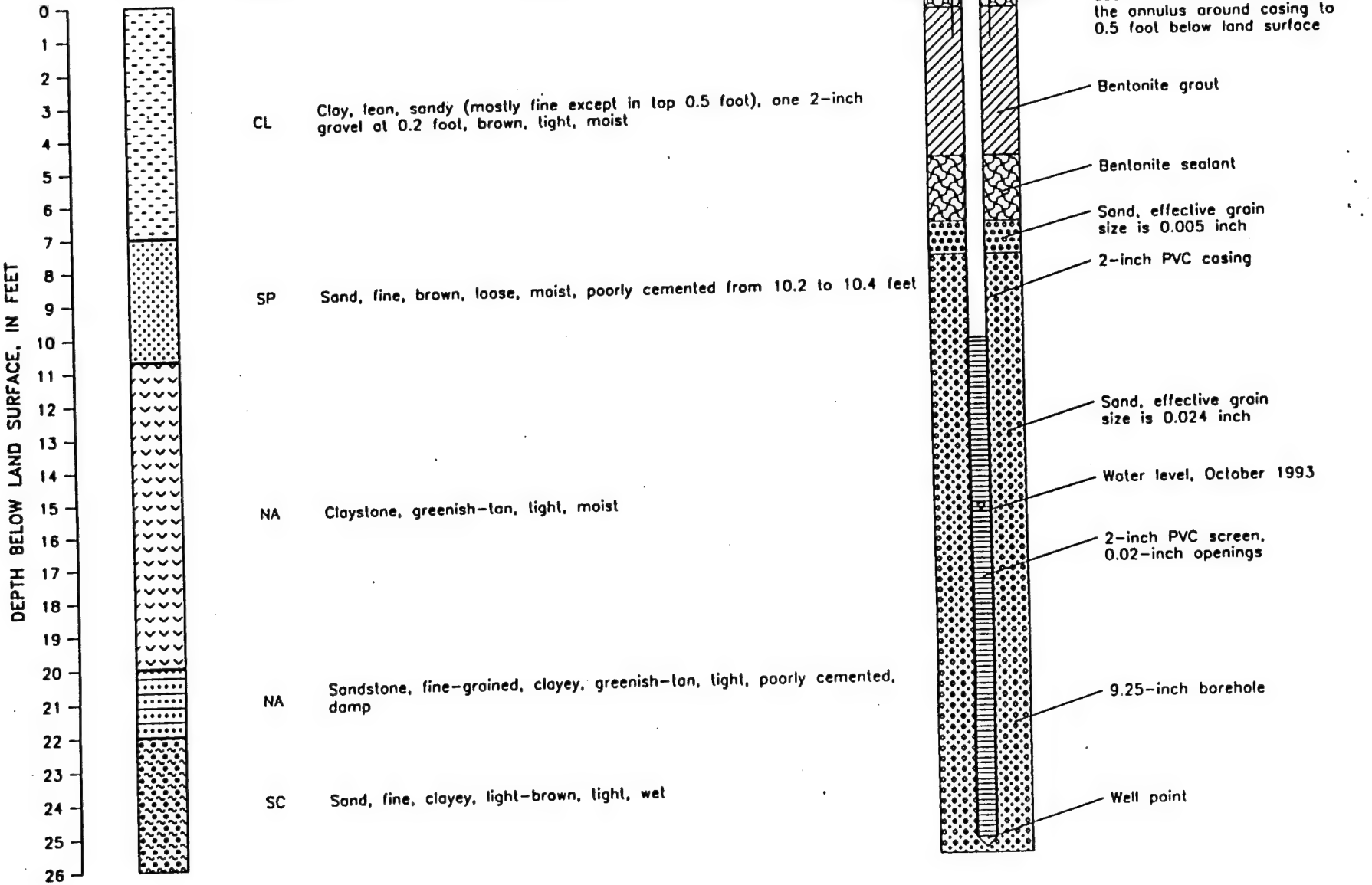
WELL 234--Continued



PBC 10-18-1994

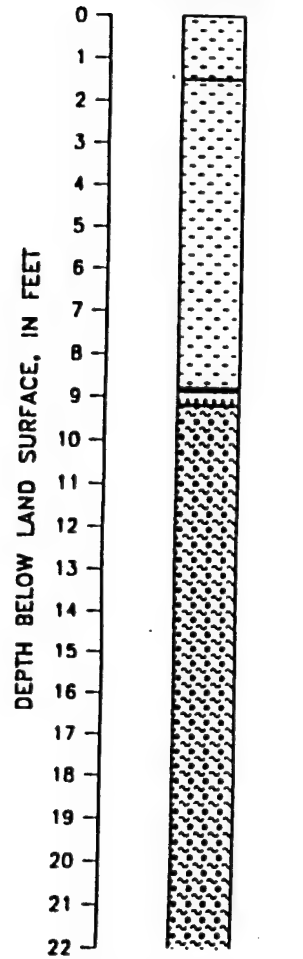
WELL 235

LAND SURFACE ELEVATION 6,129.07 FEET ABOVE SEA LEVEL



WELL 236

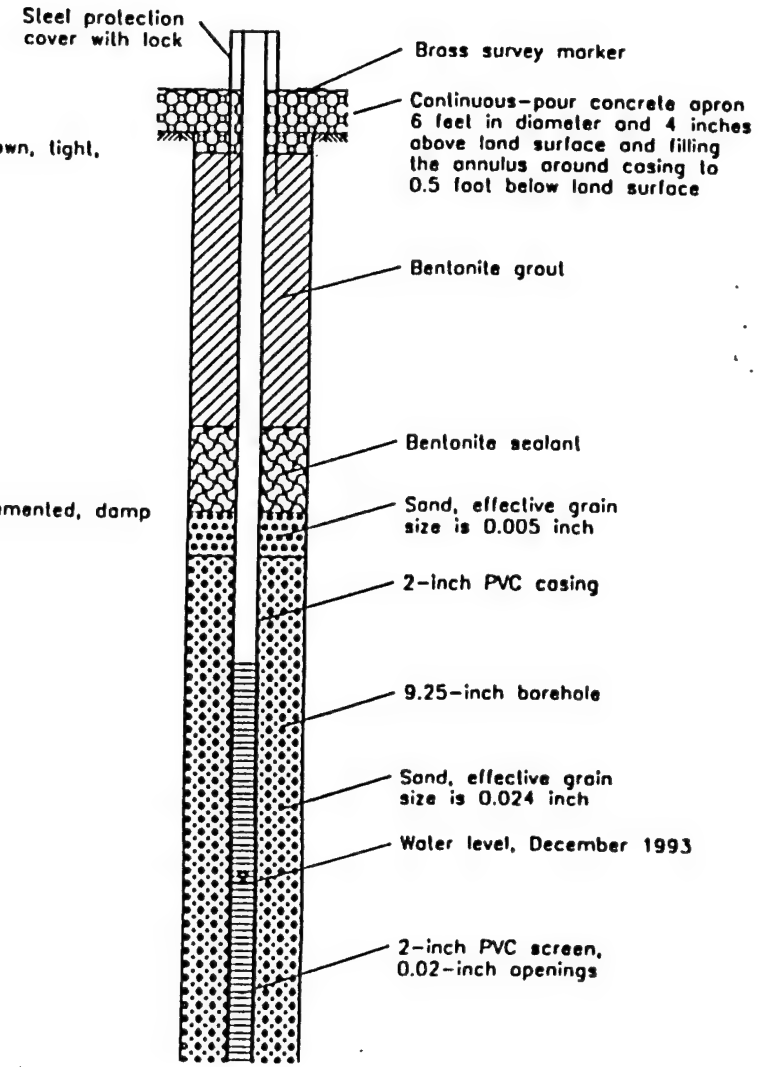
LAND SURFACE ELEVATION 6,107.33 FEET ABOVE SEA LEVEL



GROUP SYMBOL	DESCRIPTION OF CORE
CL	Clay, lean, sandy (fine to coarse), some fine gravel, brown, tight, moist, topsoil, grass roots
CL	Clay, lean, sandy (fine), tan, tight, moist
NA	Sandstone, fine-grained, clayey, tan, tight, moderately cemented, damp
SC	Sand, fine, clayey, tan, light, moist

Continued on next page

WELL CONSTRUCTION



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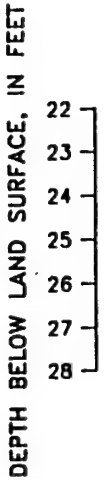
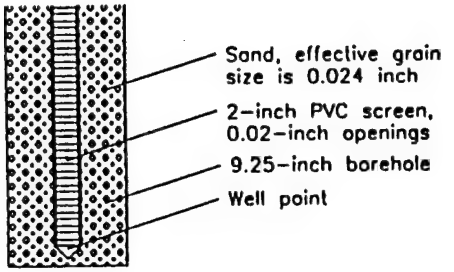
WELL 236--Continued



LITHOLOGY

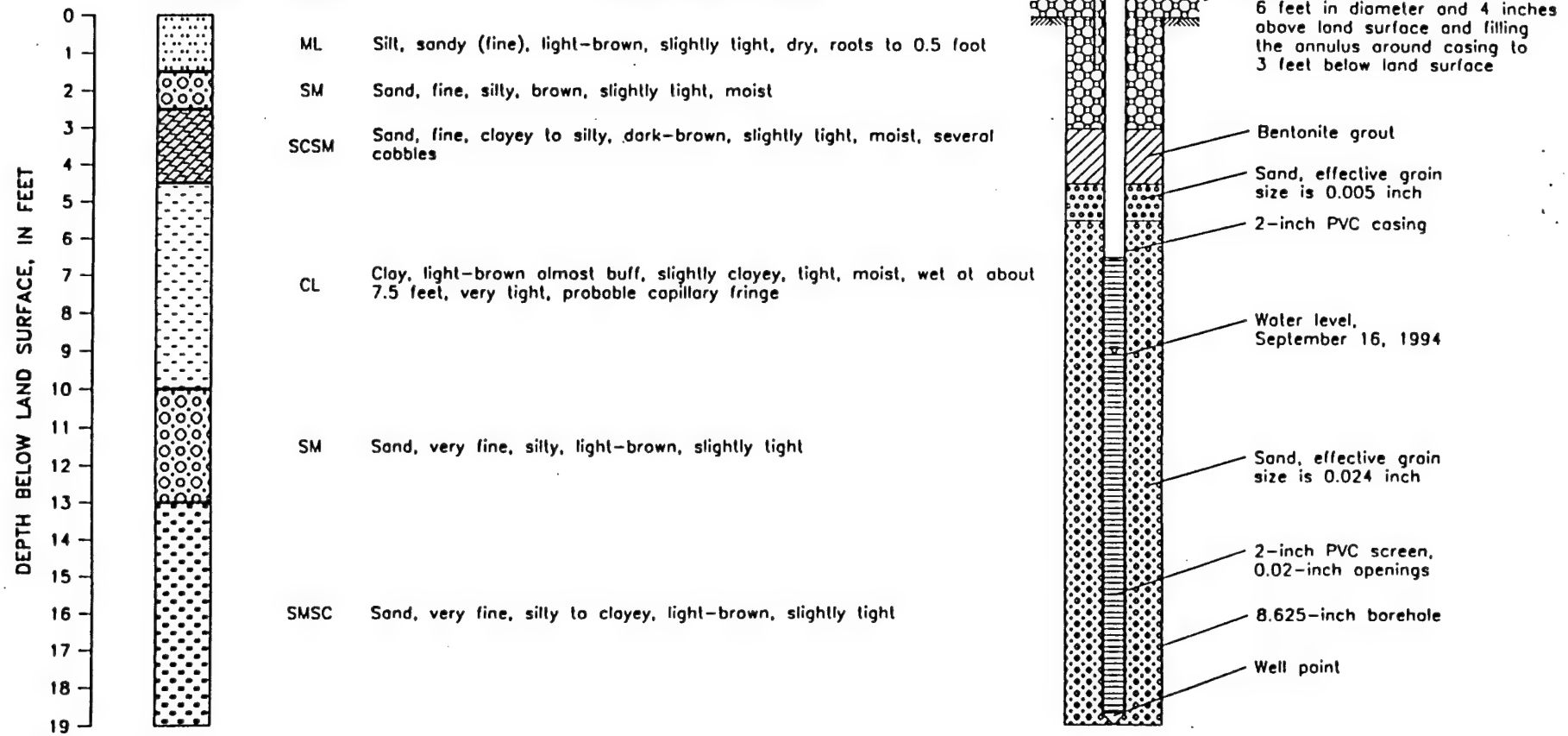
GROUP SYMBOL	DESCRIPTION OF CORE
SC	Sand, fine, clayey, tan, light, moist
NA	Claystone, tan, light, damp

WELL CONSTRUCTION



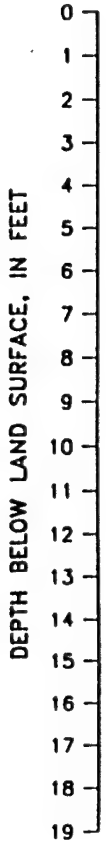
WELL 237

LAND SURFACE ELEVATION 6,116.06 FEET ABOVE SEA LEVEL



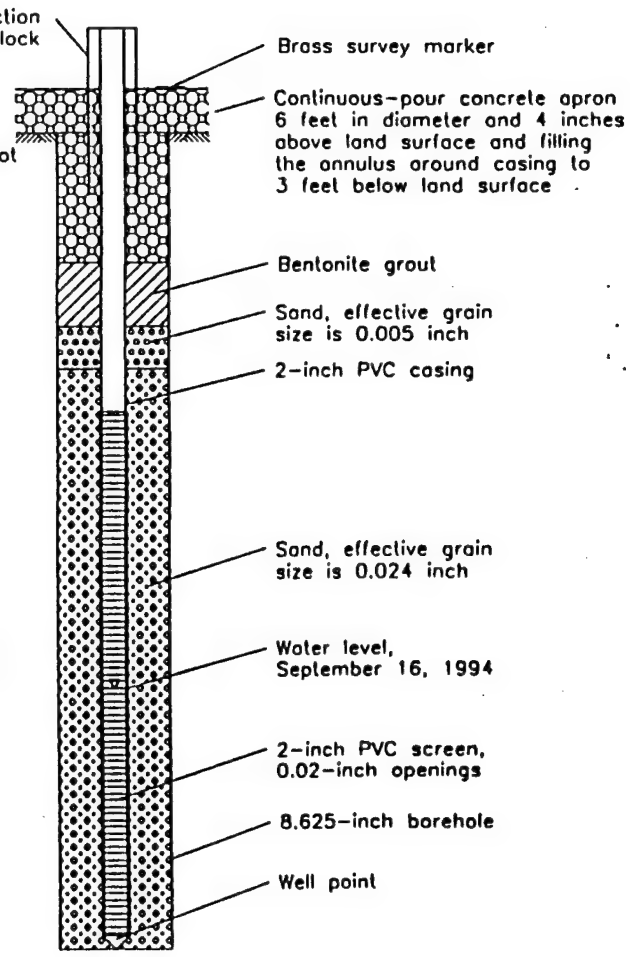
WELL 238

LAND SURFACE ELEVATION 6,113.20 FEET ABOVE SEA LEVEL



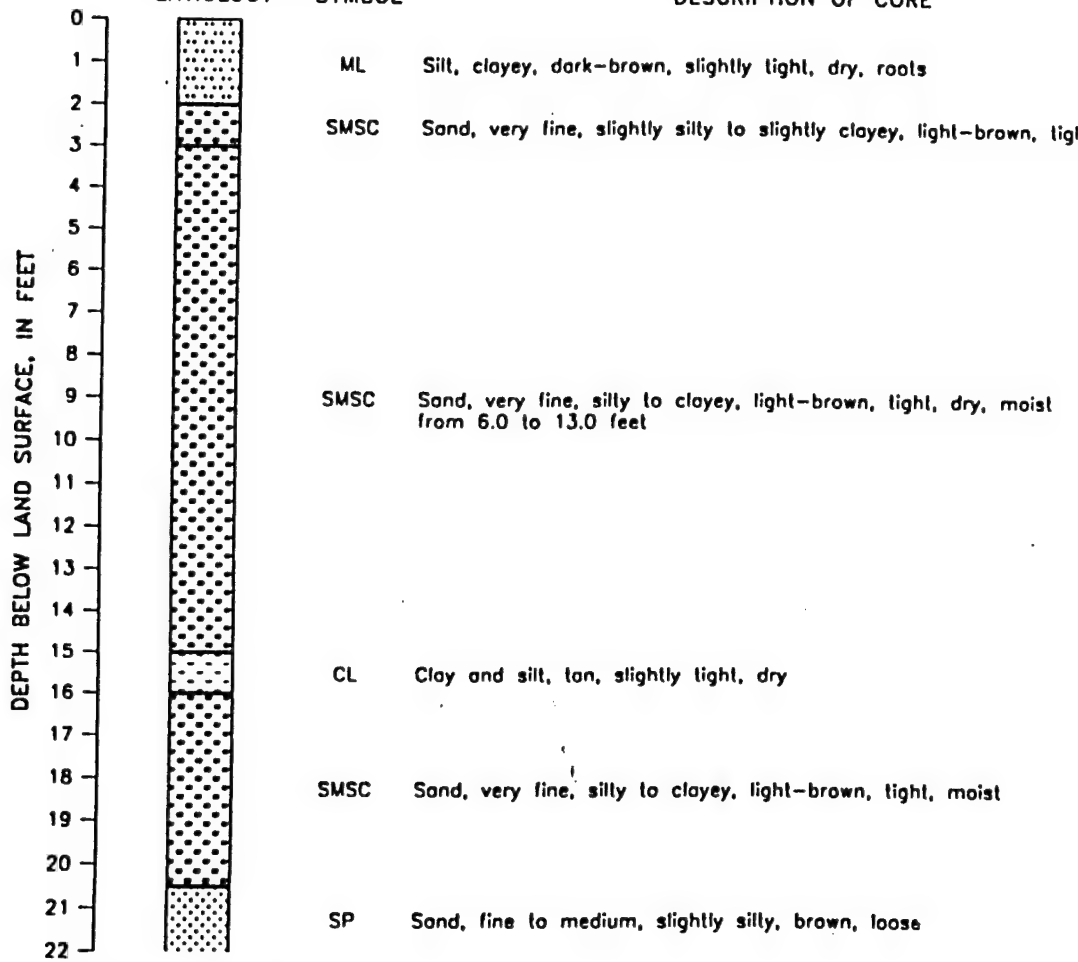
LITHOLOGY	GROUP SYMBOL	DESCRIPTION OF CORE
	ML	Silt, sandy (very fine) to clayey, brown, slightly tight, roots to 0.8 foot
	SM	Sand, very fine, silty, light-brown, slightly tight, dry
	SM	Sand, fine to coarse, silty, light-brown, slightly tight, moist
	CL	Clay, silty, tan, slightly tight, moist
	SMSC	Sand, very fine, silty to slightly clayey, light-brown, slightly tight, wet around 7.5 feet

WELL CONSTRUCTION



WELL 240

LAND SURFACE ELEVATION 6,099.04 FEET ABOVE SEA LEVEL



LITHOLOGY	GROUP SYMBOL	DESCRIPTION OF CORE
	ML	Silt, clayey, dark-brown, slightly tight, dry, roots
	SMSC	Sand, very fine, slightly silty to slightly clayey, light-brown, tight, dry
	SMSC	Sand, very fine, silty to clayey, light-brown, tight, dry, moist from 6.0 to 13.0 feet
	CL	Clay and silt, tan, slightly tight, dry
	SMSC	Sand, very fine, silty to clayey, light-brown, tight, moist
	SP	Sand, fine to medium, slightly silty, brown, loose

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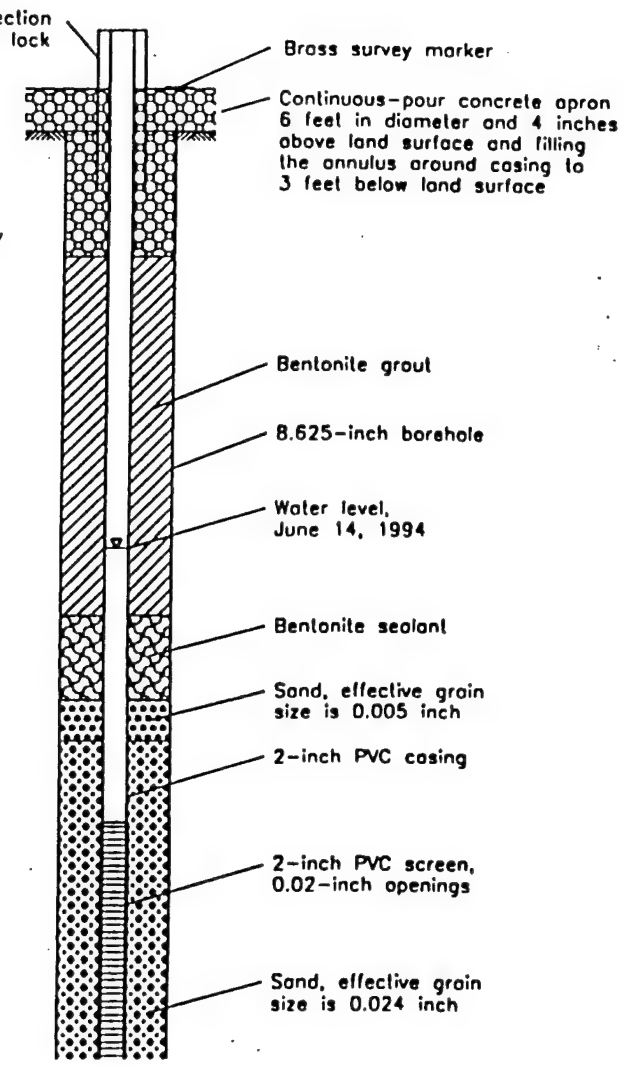
WELL CONSTRUCTION



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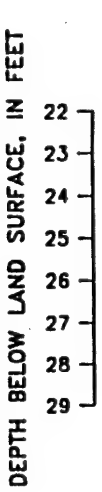
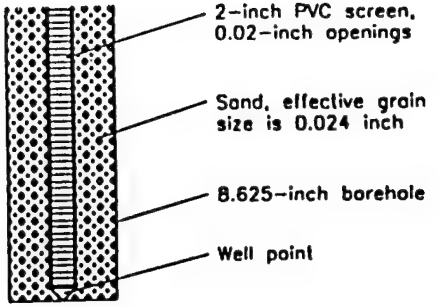
WELL 240--Continued



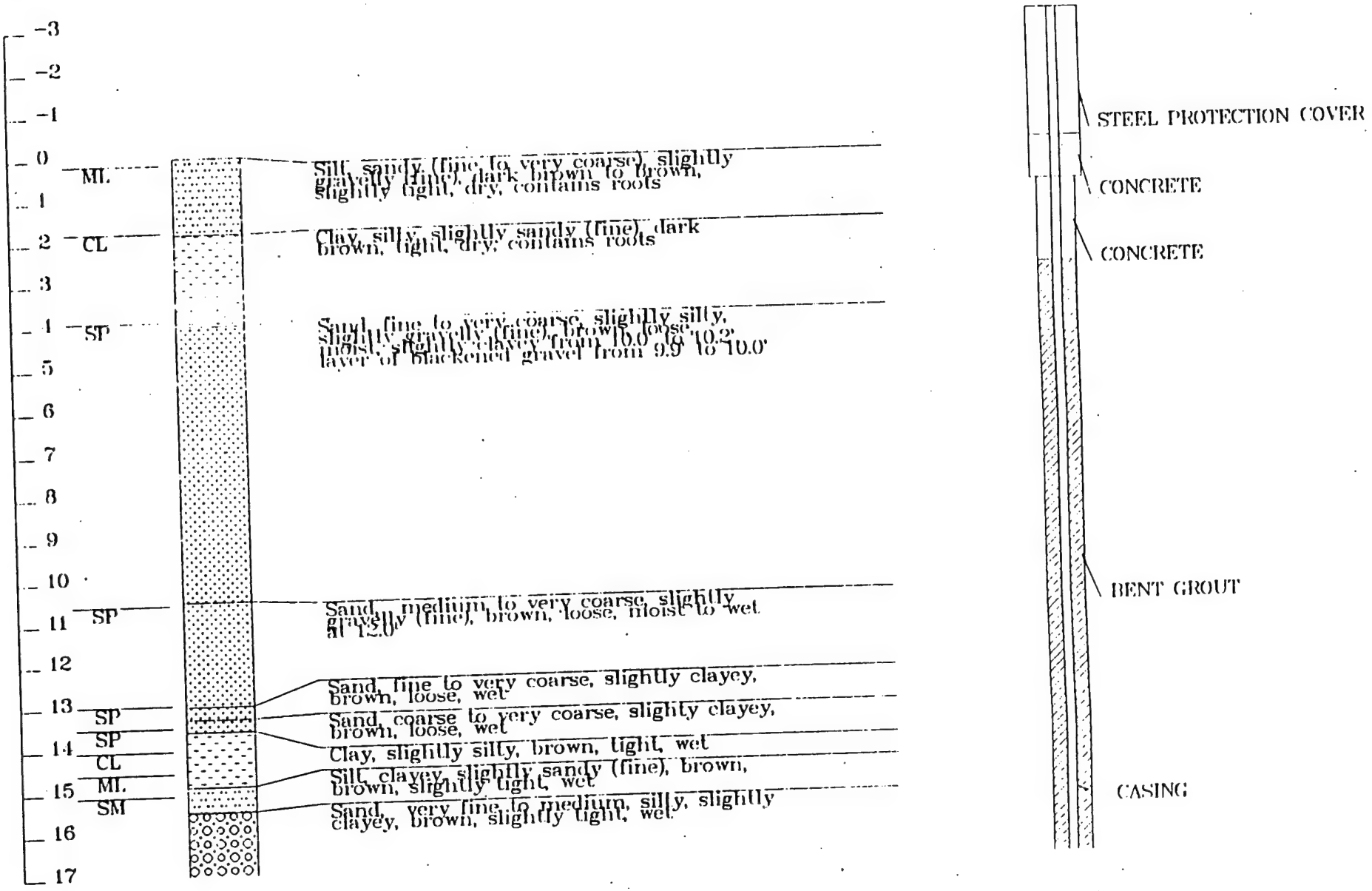
LITHOLOGY

GROUP SYMBOL	DESCRIPTION OF CORE
SP	Sand, fine to medium, slightly silty, brown, loose, light zone from 22.5 to 23.0 feet
SMSC	Sand, very fine, silty to clayey, brown, tight

WELL CONSTRUCTION



WELL 199M1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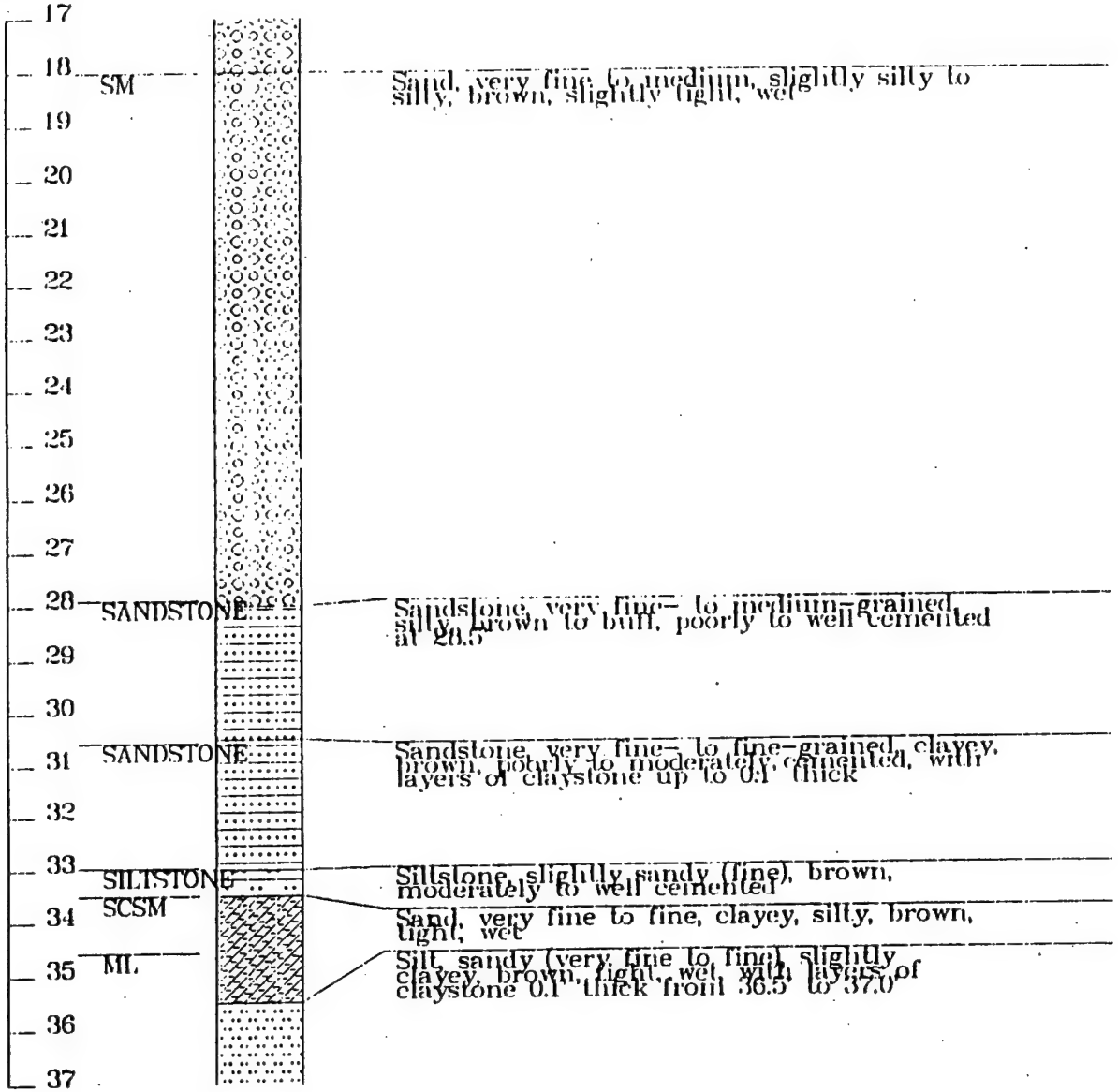
ML
CL
SP
SP
SP
CL
ML
SM
Silt, sandy (fine to very coarse), slightly gravelly (fine), dark brown to brown, slightly tight, dry, contains roots
Clay, silty, slightly sandy (fine), dark brown, tight, dry, contains roots
Sand, fine to very coarse, slightly silty, slightly gravelly (fine), brown, loose, moist, slightly clayey from 10.0' to 10.2', layer of blackened gravel from 9.9' to 10.0'
Sand, medium to very coarse, slightly gravelly (fine), brown, loose, moist to wet at 12.0'
Sand, fine to very coarse, slightly clayey, brown, loose, wet
Sand, coarse to very coarse, slightly clayey, brown, loose, wet
Clay, slightly silty, brown, tight, wet
Silt, clayey, slightly sandy (fine), brown, brown, slightly tight, wet
Sand, very fine to medium, silty, slightly clayey, brown, slightly tight, wet
STEEL PROTECTION COVER
CONCRETE
CONCRETE
BENT GROUT
CASING

WELL 199M1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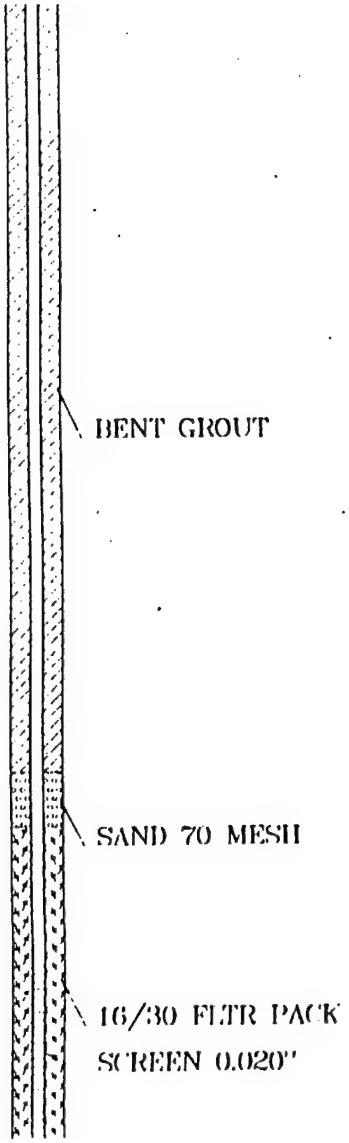
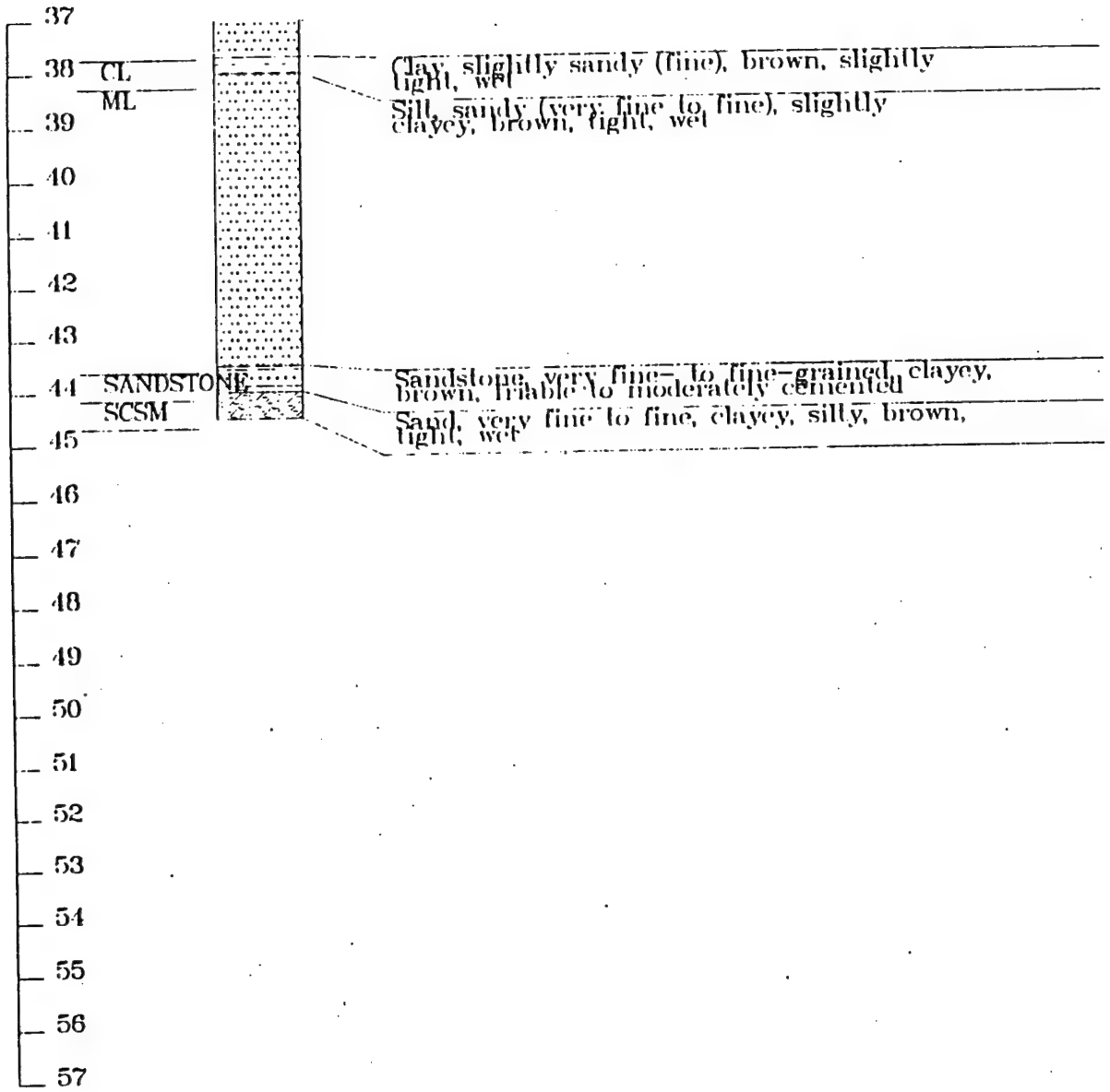
SM
SANDSTONE
SANDSTONE
SILTSTONE
SCSM
ML
Sand, very fine to medium, slightly silty to silty, brown, slightly tight, wet
Sandstone, very fine- to medium-grained, silty, brown to buff, poorly to well cemented at 28.5
Sandstone, very fine- to fine-grained, clayey, brown, poorly to moderately cemented, with layers of claystone up to 0.1' thick
Siltstone, slightly sandy (fine), brown, moderately to well cemented
Sand, very fine to fine, clayey, silty, brown, tight, wet
Silt, sandy (very fine to fine), slightly clayey, brown, tight, wet, with layers of claystone 0.1' thick from 36.5' to 37.0'


BENT GROUT
SAND 70 MESH
16/30 FLTR PACK
SCREEN 0.020"

WELL 199M1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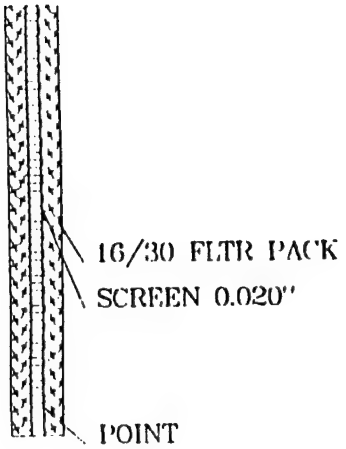
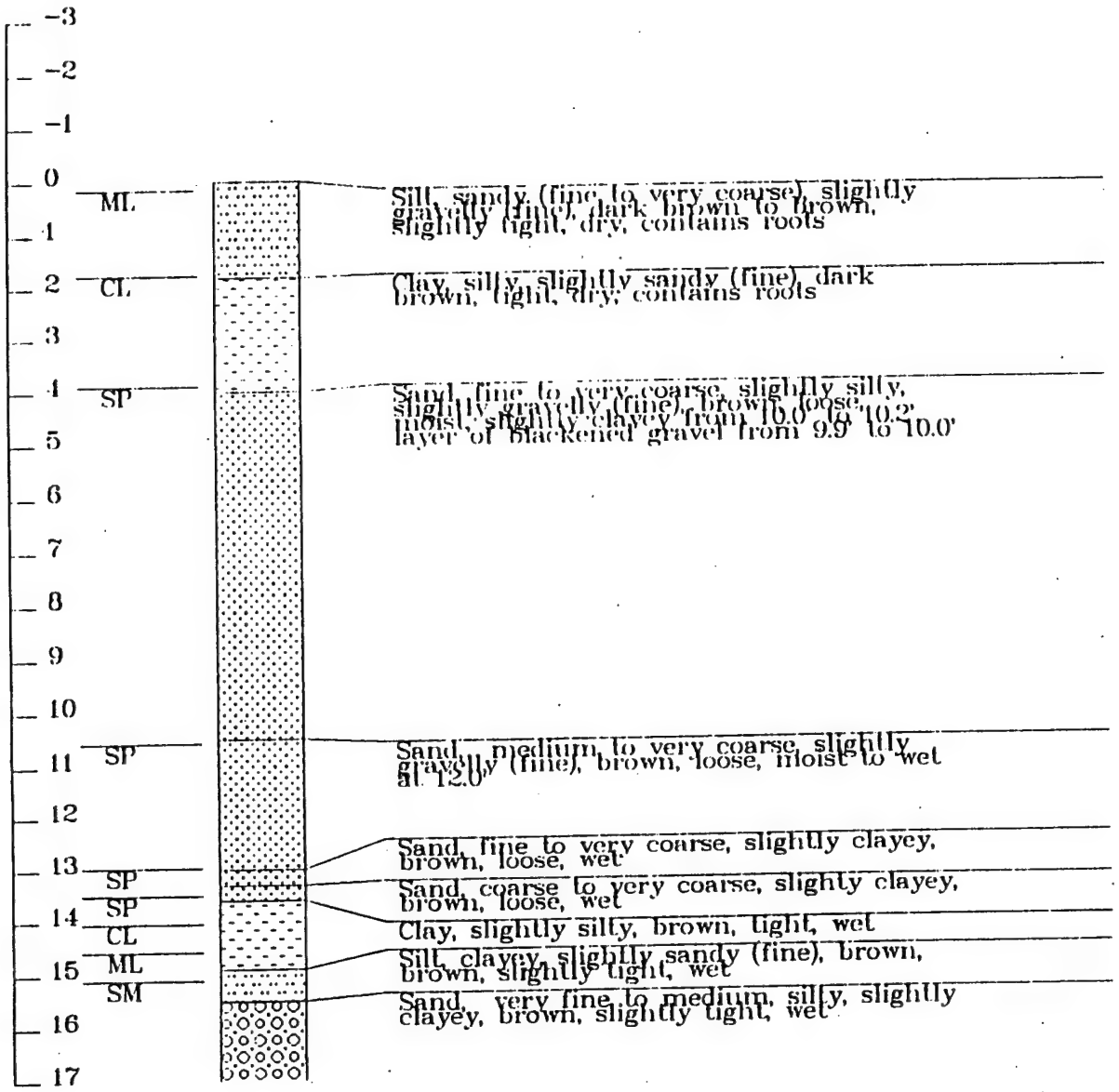
CL
ML
SANDSTONE
SCSM
Clay, slightly sandy (fine), brown, slightly light, wet
Silt, sandy (very fine to fine), slightly clayey, brown, light, wet
Sandstone, very fine- to fine-grained, clayey, brown, friable to moderately cemented
Sand, very fine to fine, clayey, silty, brown, light, wet


16/30 FLTR PACK
SCREEN 0.020"
POINT

WELL 199D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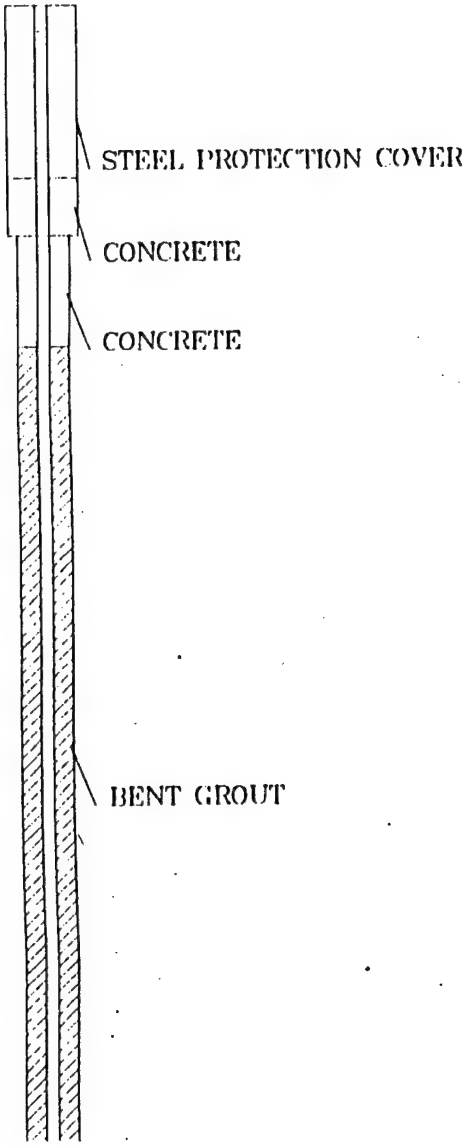
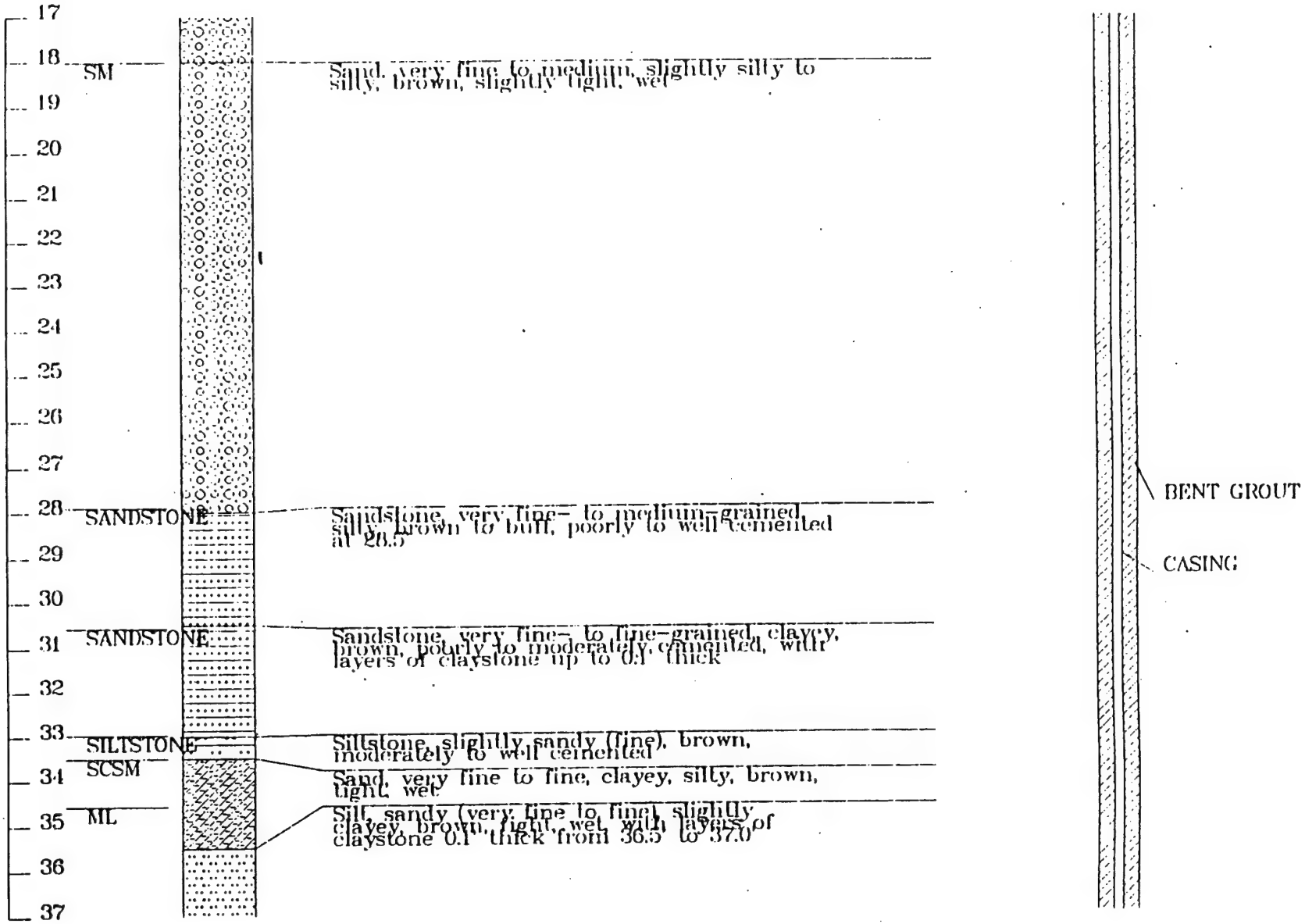
ML
CL
SP
SP
SP
SP
CL
ML
SM
Silt, sandy (fine to very coarse), slightly gravelly (fine), dark brown to brown, slightly tight, dry, contains roots
Clay, silty, slightly sandy (fine), dark brown, tight, dry, contains roots
Sand, fine to very coarse, slightly silty, slightly gravelly (fine), brown, loose, moist, slightly clayey from 10.0' to 10.2', layer of blackened gravel from 9.9' to 10.0'
Sand, medium to very coarse slightly gravelly (fine), brown, loose, moist to wet at 12.0'
Sand, fine to very coarse, slightly clayey, brown, loose, wet
Sand, coarse to very coarse, slighty clayey, brown, loose, wet
Clay, slightly silty, brown, tight, wet
Silt, clayey, slightly sandy (fine), brown, brown, slightly tight, wet
Sand, very fine to medium, silty, slightly clayey, brown, slightly tight, wet


STEEL PROTECTION COVER
CONCRETE
CONCRETE
BENT GROUT

WELL 199D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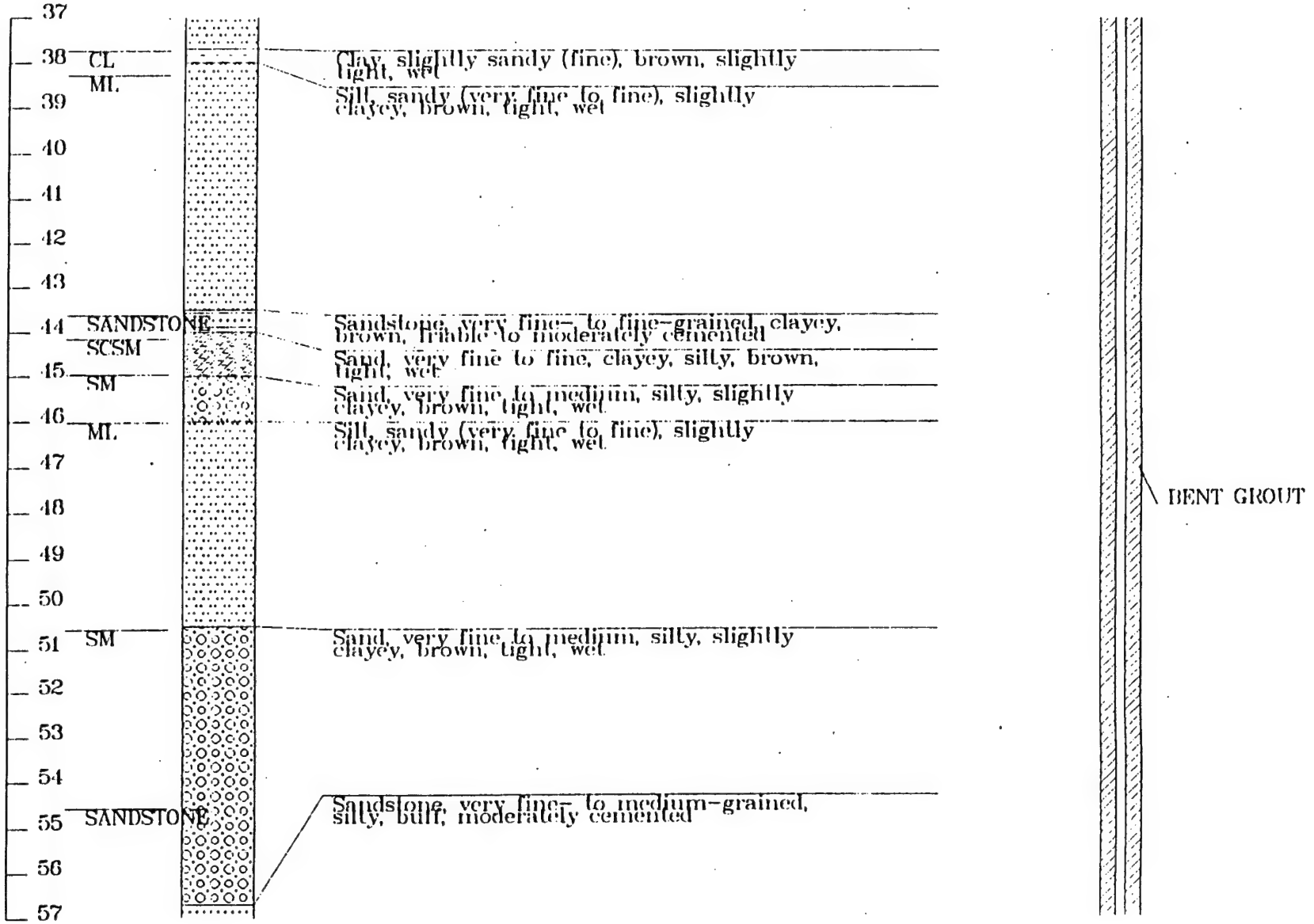
SM
SANDSTONE
SANDSTONE
SILTSTONE
SCSM
ML
Sand, very fine to medium, slightly silty to silty, brown, slightly tight, wet
Sandstone, very fine- to medium-grained, silty, brown to buff, poorly to well cemented at 28.5
Sandstone, very fine- to fine-grained, clayey, brown, poorly to moderately cemented, with layers of claystone up to 0.1' thick
Siltstone, slightly sandy (fine), brown, moderately to well cemented
Sand, very fine to fine, clayey, silty, brown, tight, wet
Silt, sandy (very fine to fine), slightly clayey, brown, tight, wet, with layers of claystone 0.1' thick from 36.5' to 37.0
BENT GROUT
CASING

WELL 199D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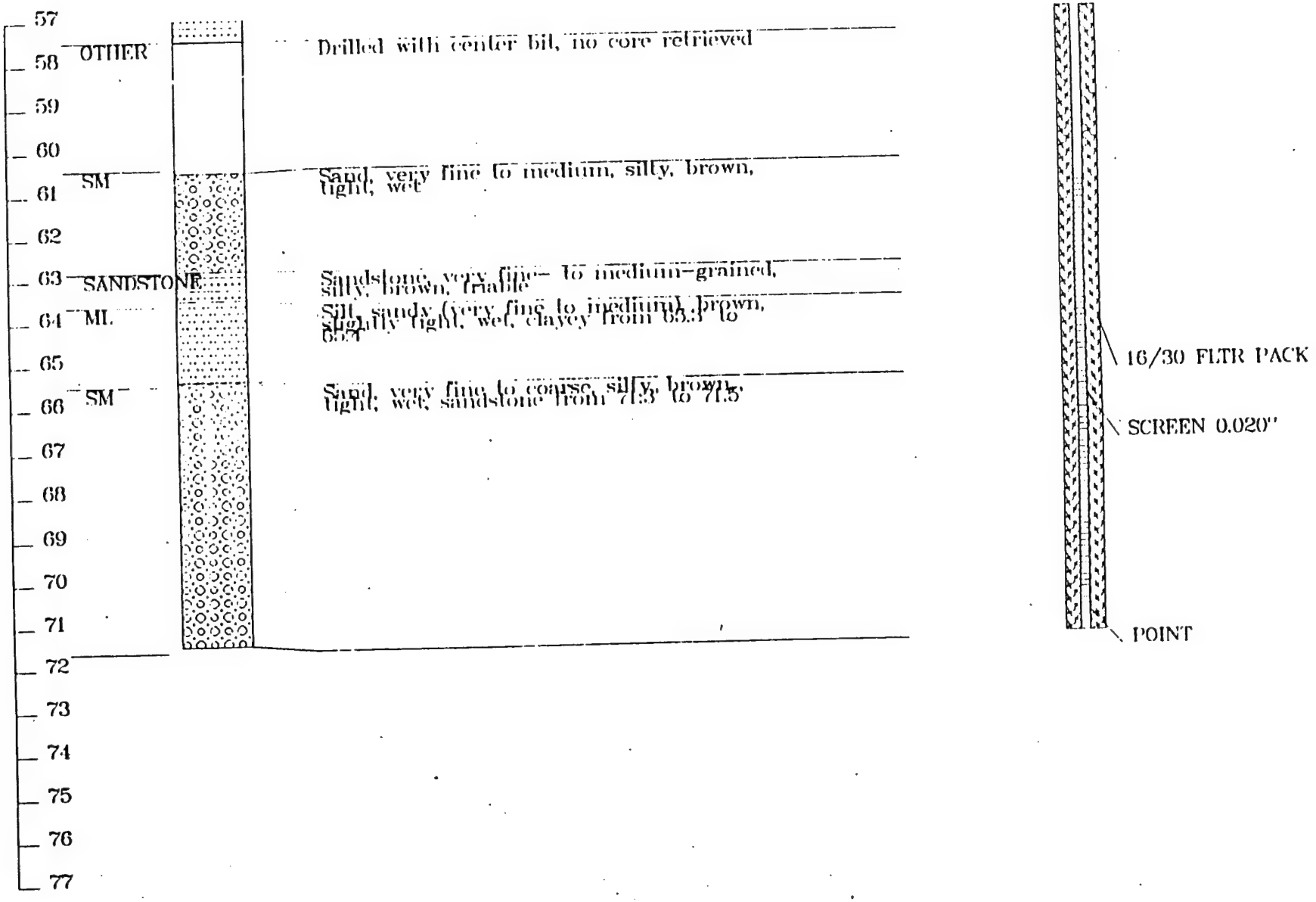
SANDSTONE
Clay, slightly sandy (fine), brown, slightly light, wet
Silt, sandy (very fine to fine), slightly clayey, brown, light, wet
Sandstone, very fine- to fine-grained, clayey, brown, friable to moderately cemented
Sand, very fine to fine, clayey, silty, brown, light, wet
Sand, very fine to medium, silty, slightly clayey, brown, light, wet
Silt, sandy (very fine to fine), slightly clayey, brown, light, wet
Sand, very fine to medium, silty, slightly clayey, brown, light, wet
Sandstone, very fine- to medium-grained, silty, buff, moderately cemented
BENT GROUT

WELL 199D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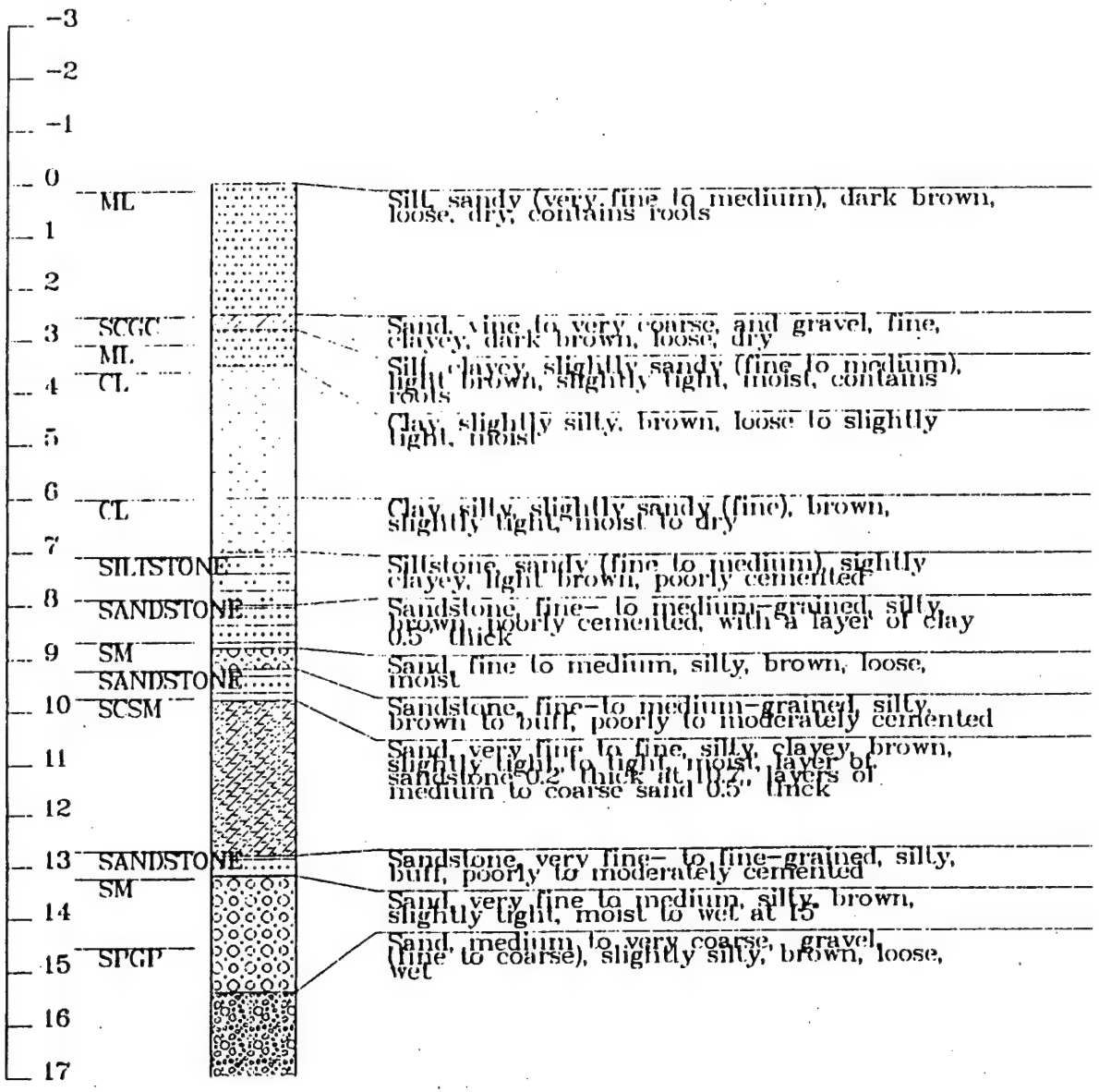
OTHER
SM
SANDSTONE
ML
SM
Drilled with center bit, no core retrieved
Sand, very fine to medium, silty, brown, light, wet
Sandstone, very fine- to medium-grained, silty, brown, friable
Silt, sandy (very fine to medium), brown, slightly light, wet, clayey from 65.3' to 65.4
Sand, very fine to coarse, silty, brown, light, wet, sandstone from 71.3' to 71.5
16/30 FLTR PACK
SCREEN 0.020"
POINT

WELL 209M1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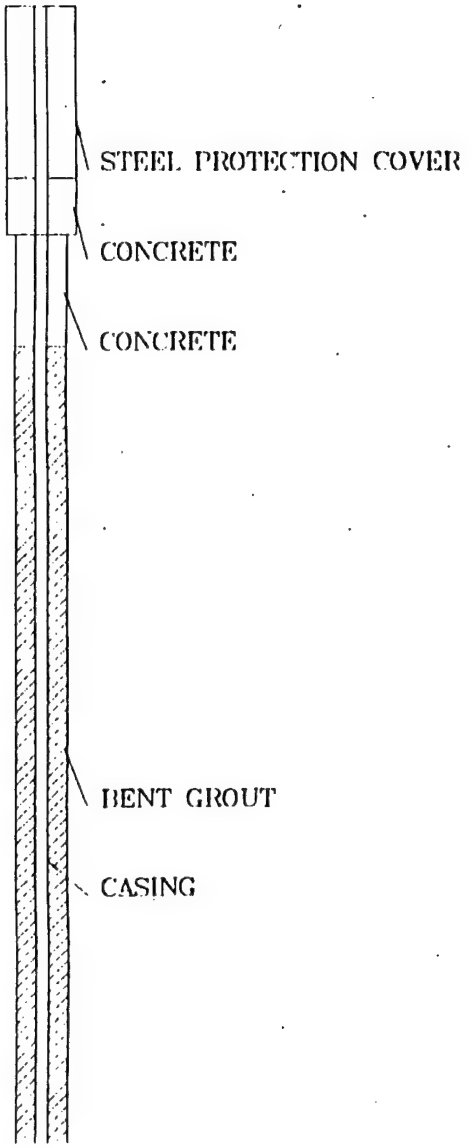
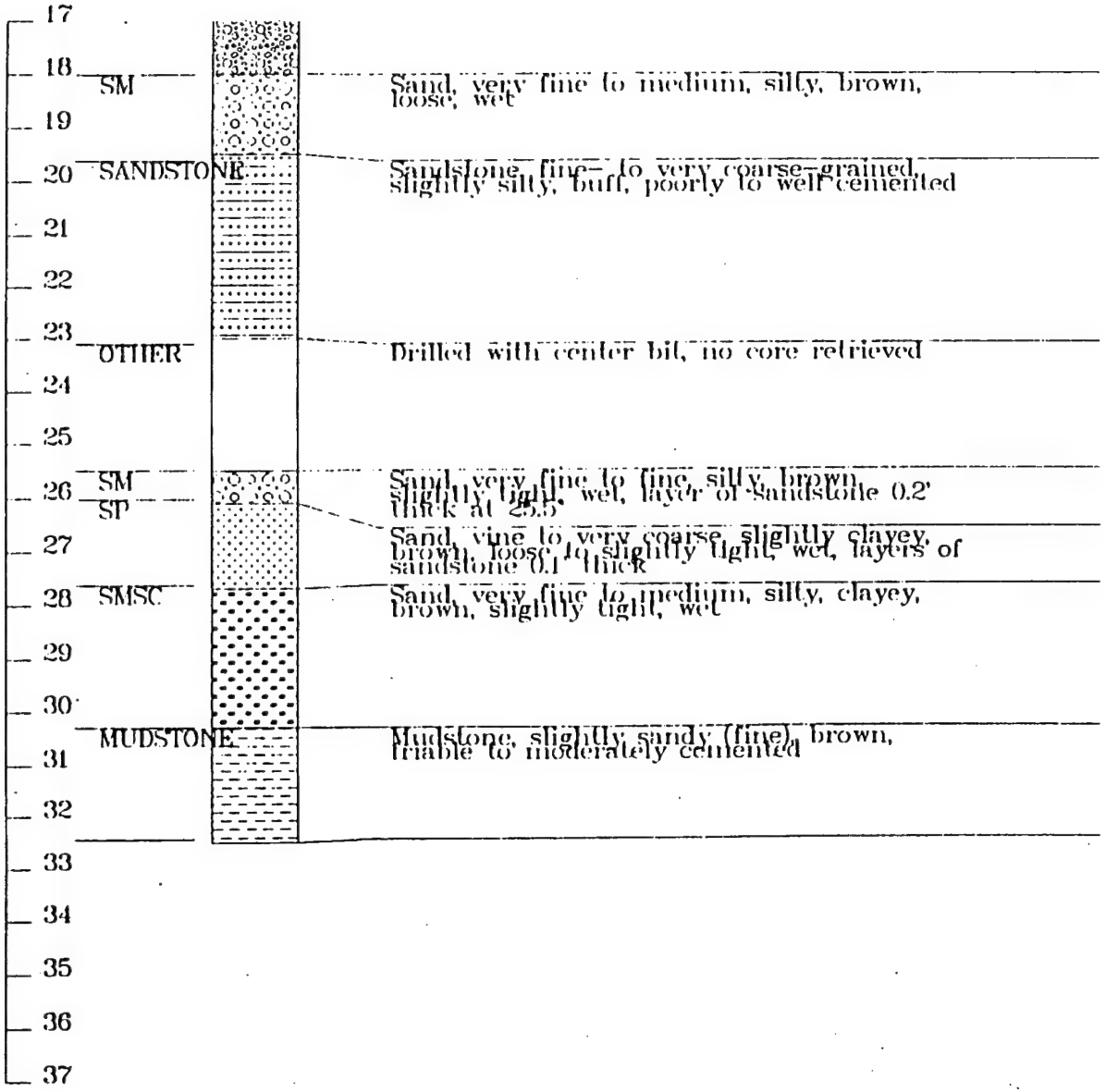
SM
SPGP
Silt, sandy (very fine to medium), dark brown, loose, dry, contains roots
Sand, fine to very coarse, and gravel, fine, clayey, dark brown, loose, dry
Silt, clayey, slightly sandy (fine to medium), light brown, slightly tight, moist, contains roots
Clay, slightly silty, brown, loose to slightly tight, moist
Clay, silty, slightly sandy (fine), brown, slightly tight, moist to dry
Siltstone, sandy (fine to medium), slightly clayey, light brown, poorly cemented
Sandstone, fine- to medium-grained, silty, brown, poorly cemented, with a layer of clay 0.5" thick
Sand, fine to medium, silty, brown, loose, moist
Sandstone, fine- to medium-grained, silty, brown to buff, poorly to moderately cemented
Sand, very fine to fine, silty, clayey, brown, slightly tight to tight, moist, layer of sandstone 0.2" thick at 10.7, layers of medium to coarse sand 0.5" thick
Sandstone, very fine- to fine-grained, silty, buff, poorly to moderately cemented
Sand, very fine to medium, silty, brown, slightly tight, moist to wet at 15
Sand, medium to very coarse, gravel (fine to coarse), slightly silty, brown, loose, wet


STEEL PROTECTION COVER
CONCRETE
CONCRETE
BENT GROUT
CASING

WELL 209M1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SM
SANDSTONE
OTHER
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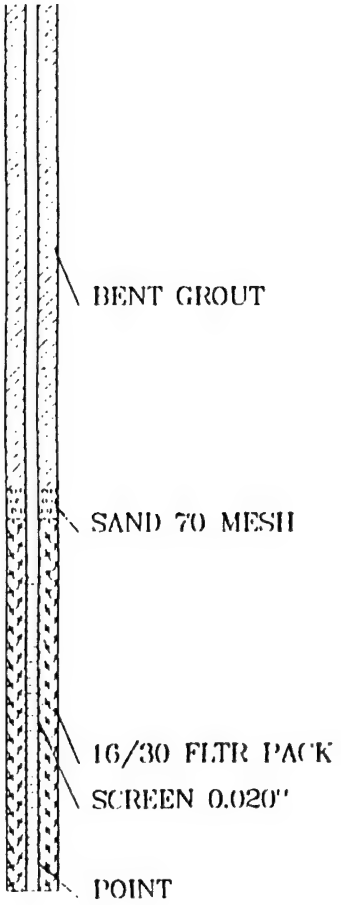
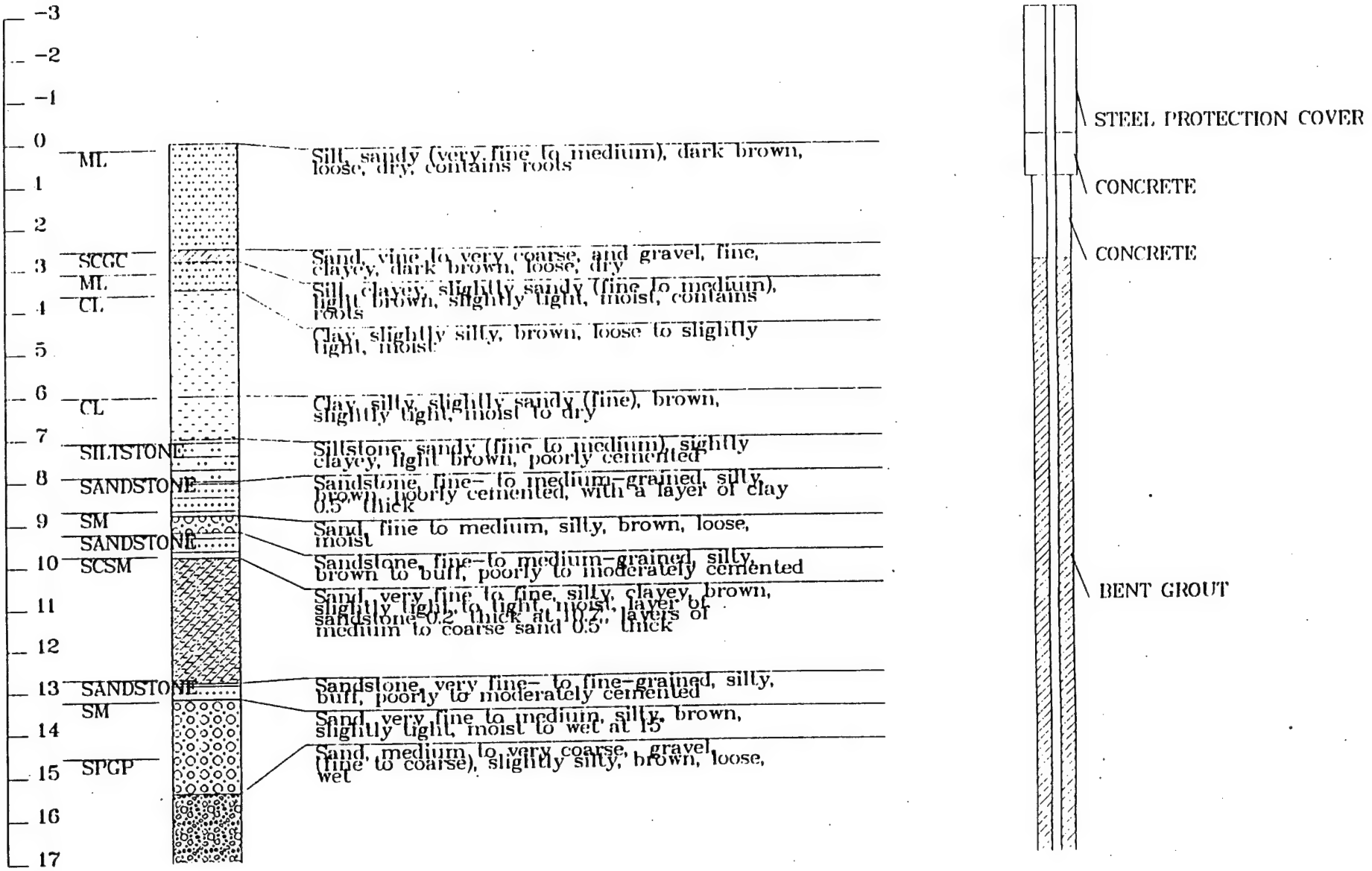
SP
SMSC
MUDSTONE
Sand, very fine to medium, silty, brown, loose, wet
Sandstone fine- to very coarse-grained, slightly silty, buff, poorly to well cemented
Drilled with center bit, no core retrieved
Sand, very fine to fine, silty, brown, slightly tight, wet, layer of sandstone 0.2' thick at 25.5'
Sand, fine to very coarse, slightly clayey, brown, loose to slightly tight, wet, layers of sandstone 0.1' thick
Sand, very fine to medium, silty, clayey, brown, slightly tight, wet
Mudstone, slightly sandy (fine), brown, friable to moderately cemented


BENT GROUT
SAND 70 MESH
16/30 FLTR PACK
SCREEN 0.020"
POINT

WELL 209D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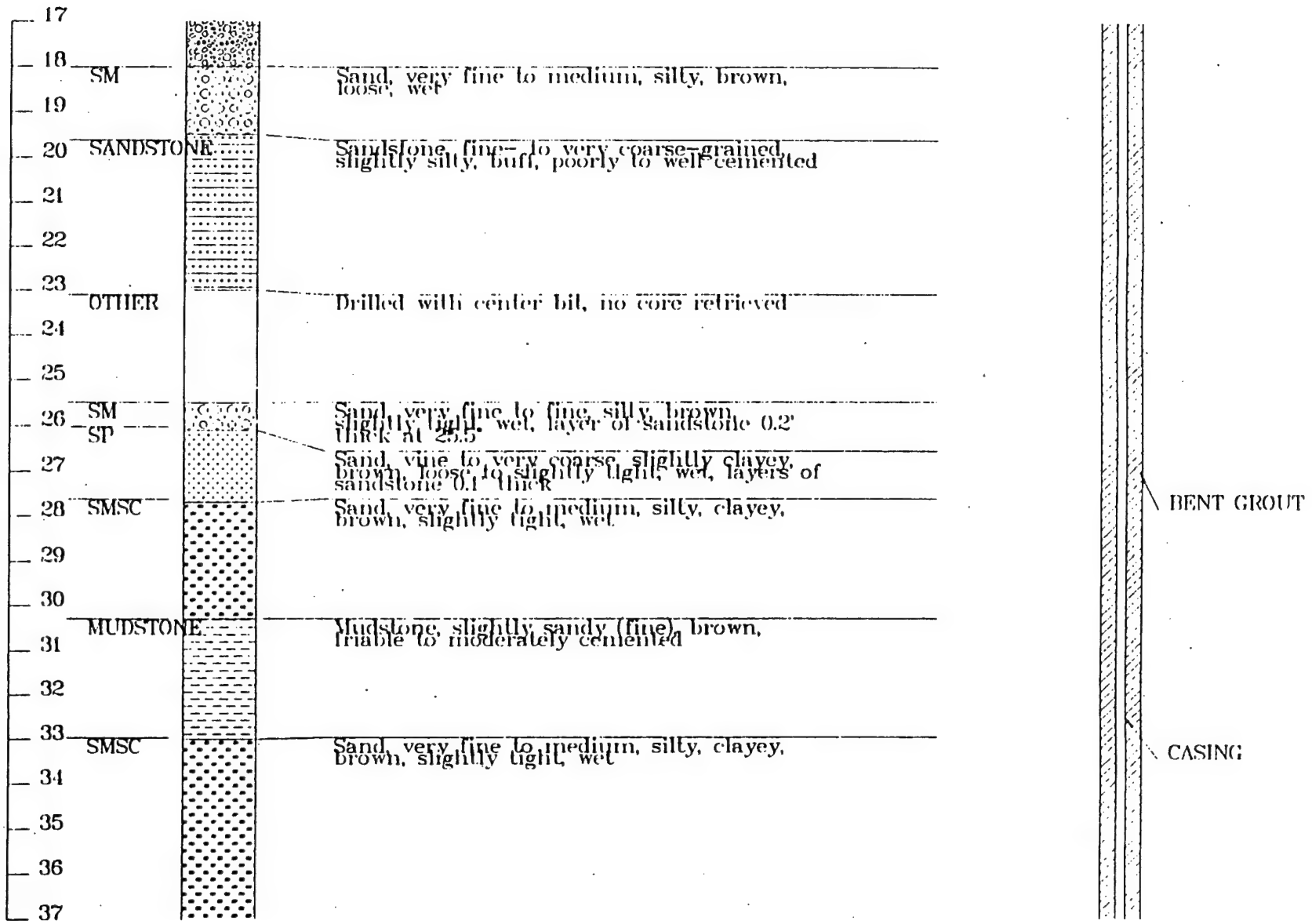
SPGP
Silt, sandy (very fine to medium), dark brown, loose, dry, contains roots
Sand, vine to very coarse, and gravel, fine, clayey, dark brown, loose, dry
Silt, clayey, slightly sandy (fine to medium), light brown, slightly tight, moist, contains roots
Clay, slightly silty, brown, loose to slightly tight, moist
Clay, silty, slightly sandy (fine), brown, slightly tight, moist to dry
Siltstone, sandy (fine to medium), slightly clayey, light brown, poorly cemented
Sandstone, fine- to medium-grained, silty, brown, poorly cemented, with a layer of clay 0.5" thick
Sand, fine to medium, silty, brown, loose, moist
Sandstone, fine- to medium-grained, silty, brown to buff, poorly to moderately cemented
Sand, very fine to fine, silty, clayey, brown, slightly tight, to light, moist, layer of sandstone 0.2" thick at 10.7', layers of medium to coarse sand 0.5" thick
Sandstone, very fine- to fine-grained, silty, buff, poorly to moderately cemented
Sand, very fine to medium, silty, brown, slightly tight, moist to wet at 15'
Sand, medium to very coarse, gravel (fine to coarse), slightly silty, brown, loose, wet
STEEL PROTECTION COVER
CONCRETE
CONCRETE
BENT GROUT

WELL 209D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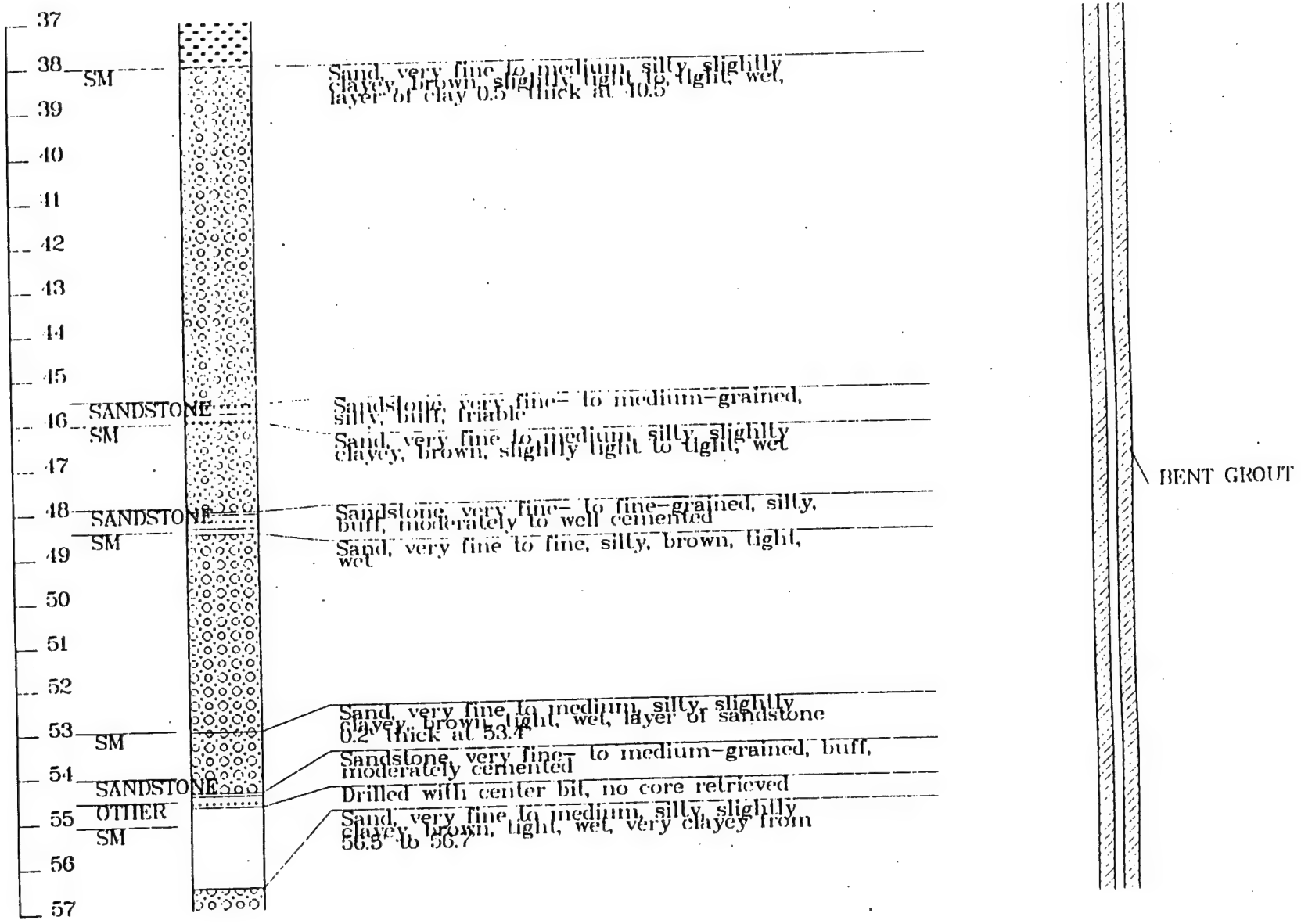
SM
SANDSTONE
OTHER
SM
SP
SMSC
MUDSTONE
SMSC
Sand, very fine to medium, silty, brown, loose, wet
Sandstone, fine- to very coarse-grained, slightly silty, buff, poorly to well cemented
Drilled with center bit, no core retrieved
Sand, very fine to fine, silty, brown, slightly tight, wet, layer of sandstone 0.2' thick at 25.5
Sand, fine to very coarse, slightly clayey, brown, loose to slightly tight, wet, layers of sandstone 0.1' thick
Sand, very fine to medium, silty, clayey, brown, slightly tight, wet
Mudstone, slightly sandy (fine), brown, friable to moderately cemented
Sand, very fine to medium, silty, clayey, brown, slightly tight, wet
BENT GROUT
CASING

WELL 209D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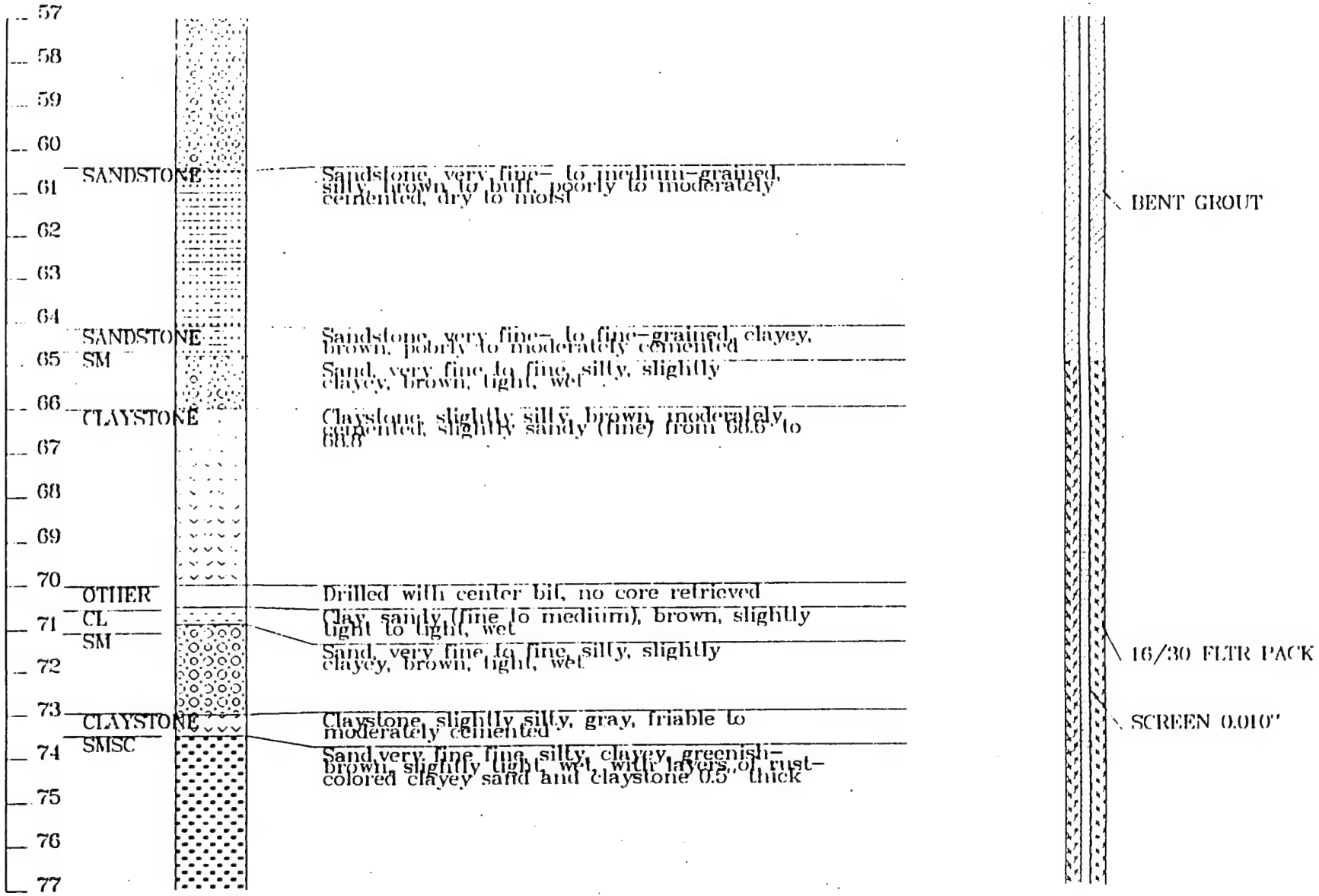
SM
SANDSTONE
SM
SANDSTONE
SM
SM
SANDSTONE
OTHER
SM
Sand, very fine to medium, silty, slightly clayey, brown slightly light to light, wet, layer of clay 0.5' thick at 40.5'
Sandstone, very fine- to medium-grained, silty, buff, friable
Sand, very fine to medium, silty, slightly clayey, brown, slightly light to light, wet
Sandstone, very fine- to fine-grained, silty, buff, moderately to well cemented
Sand, very fine to fine, silty, brown, light, wet
Sand, very fine to medium, silty, slightly clayey, brown, light, wet, layer of sandstone 0.2' thick at 53.4'
Sandstone, very fine- to medium-grained, buff, moderately cemented
Drilled with center bit, no core retrieved
Sand, very fine to medium, silty, slightly clayey, brown, light, wet, very clayey from 56.5' to 56.7'
BENT GROUT

WELL 209D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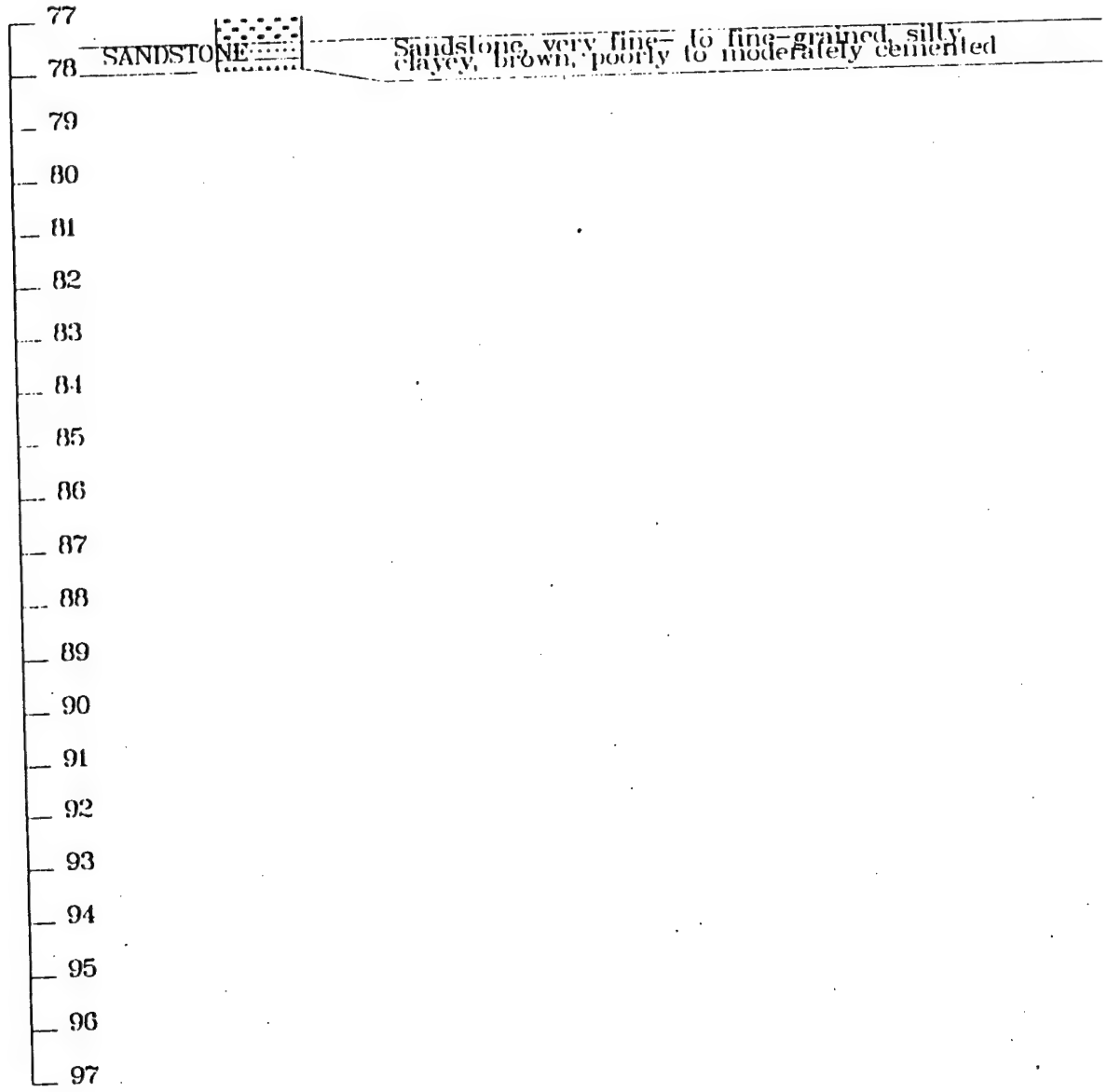
SANDSTONE
SANDSTONE
SM
CLAYSTONE
OTHER
CL
SM
CLAYSTONE
SMSC
Sandstone, very fine- to medium-grained, silty, brown to buff, poorly to moderately cemented, dry to moist
Sandstone, very fine- to fine-grained, clayey, brown, poorly to moderately cemented
Sand, very fine to fine, silty, slightly clayey, brown, light, wet
Claystone, slightly silty, brown, moderately cemented, slightly sandy (fine) from 68.6 to 68.8
Drilled with center bit, no core retrieved
Clay, sandy (fine to medium), brown, slightly light to light, wet
Sand, very fine to fine, silty, slightly clayey, brown, light, wet
Claystone, slightly silty, gray, friable to moderately cemented
Sand very fine fine, silty, clayey, greenish-brown, slightly light, wet, with layers of rust-colored clayey sand and claystone 0.5" thick
BENT GROUT
16/30 FLTR PACK
SCREEN 0.010"

WELL 209D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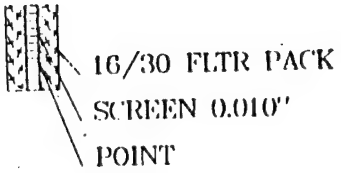
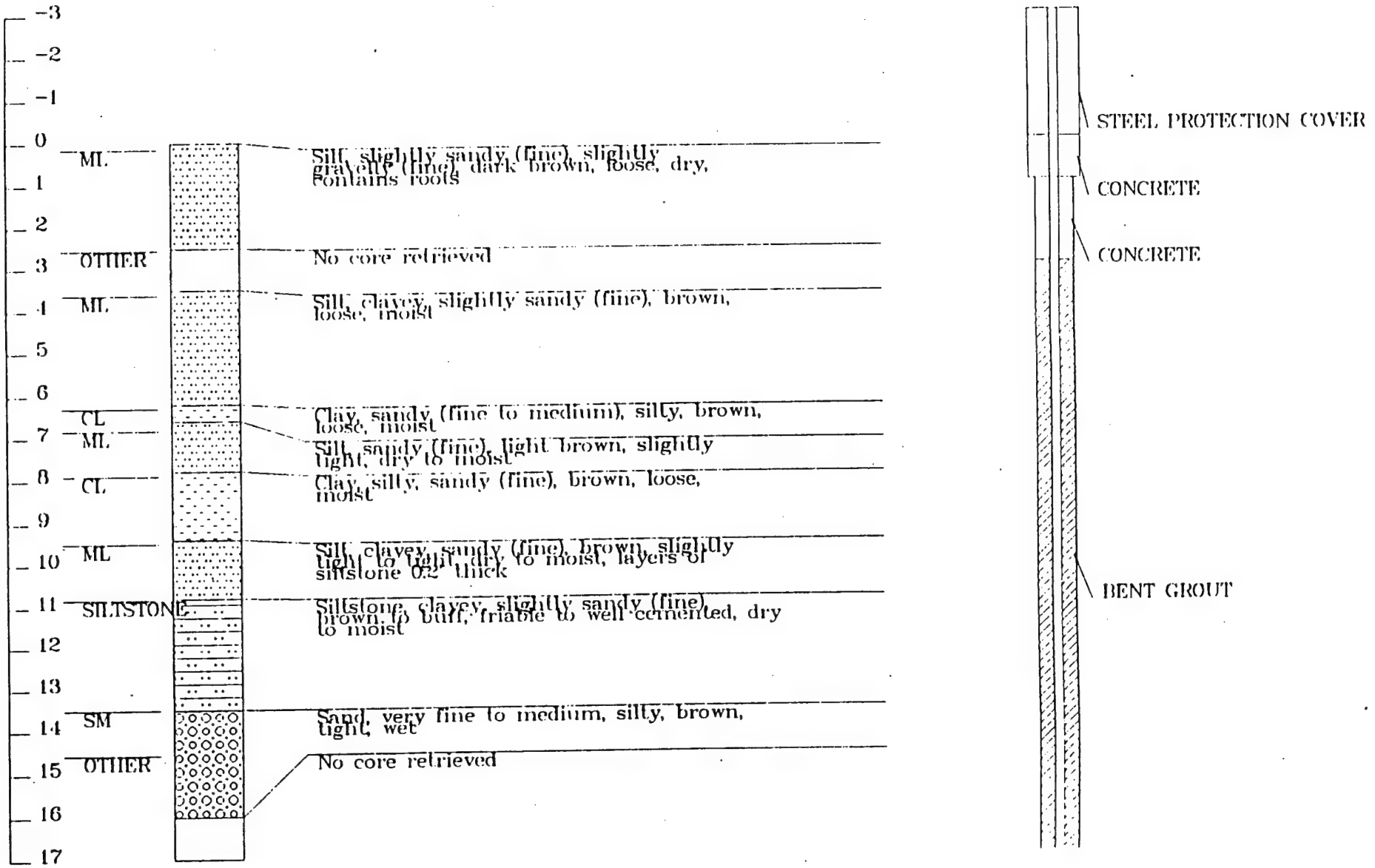
SANDSTONE
Sandstone, very fine- to fine-grained, silty, clayey, brown, poorly to moderately cemented


16/30 FLTR PACK
SCREEN 0.010"
POINT

WELL 210M1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ML
OTHER
ML
CL
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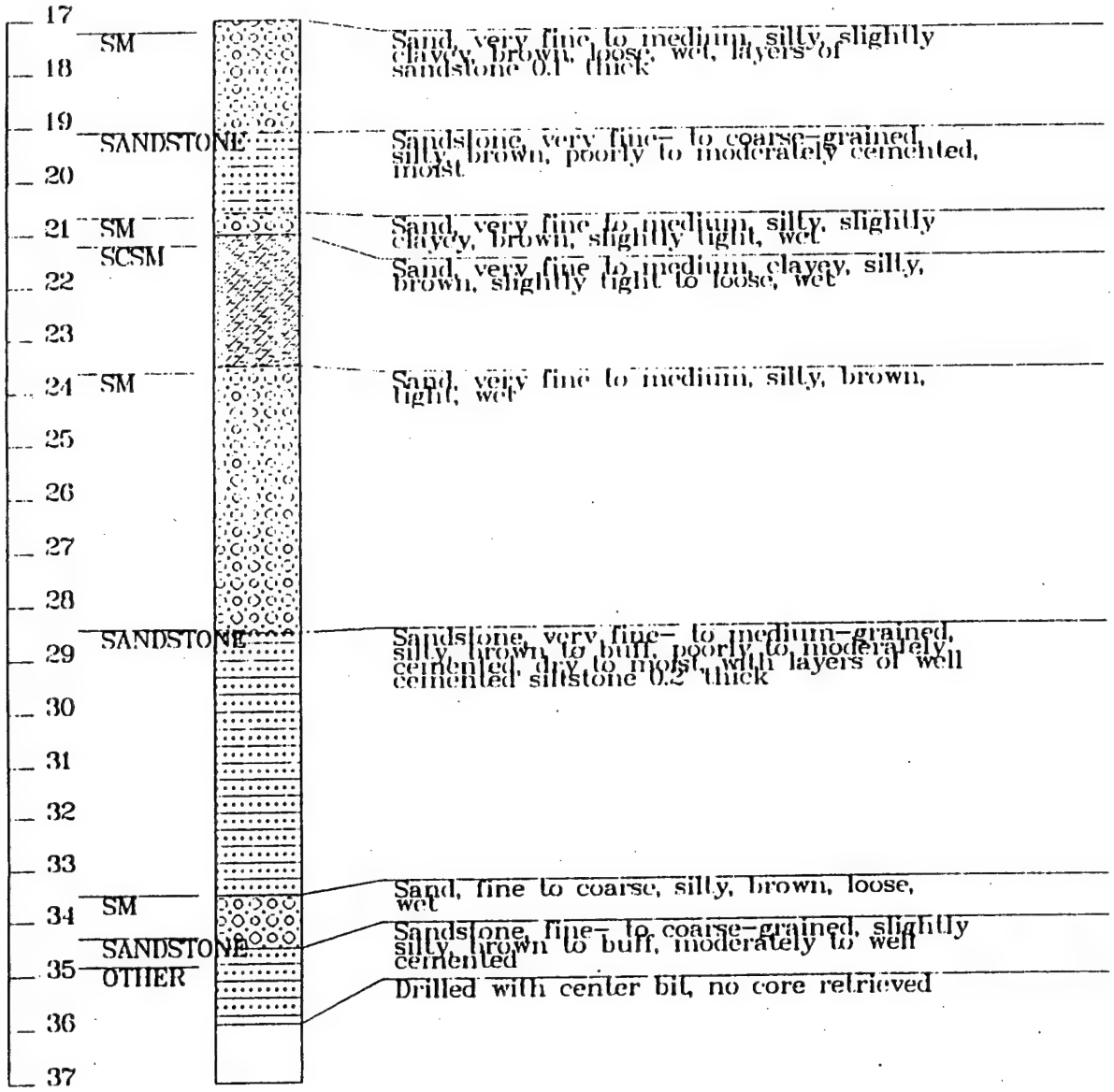
ML
SILTSTONE
SM
OTHER
Silt, slightly sandy (fine), slightly gravelly (fine), dark brown, loose, dry, contains roots
No core retrieved
Silt, clayey, slightly sandy (fine), brown, loose, moist
Clay, sandy (fine to medium), silty, brown, loose, moist
Silt, sandy (fine), light brown, slightly light, dry to moist
Clay, silty, sandy (fine), brown, loose, moist
Silt, clayey, sandy (fine), brown, slightly light to light, dry to moist, layers of siltstone 0.2" thick
Siltstone, clayey, slightly sandy (fine), brown to buff, friable to well cemented, dry to moist
Sand, very fine to medium, silty, brown, light, wet
No core retrieved
STEEL PROTECTION COVER
CONCRETE
CONCRETE
BENT GROUT

1

WELL 210M1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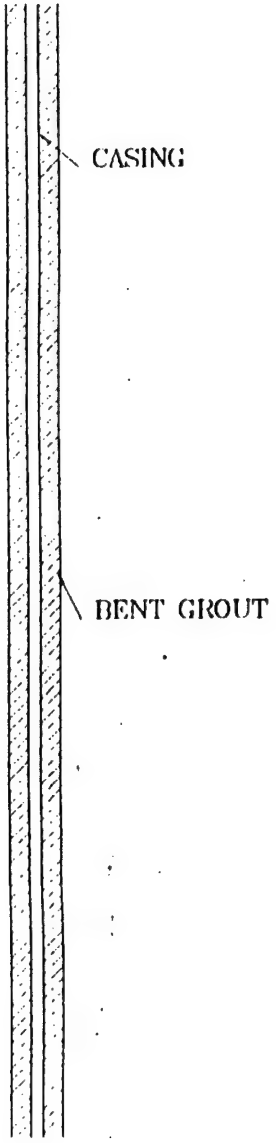
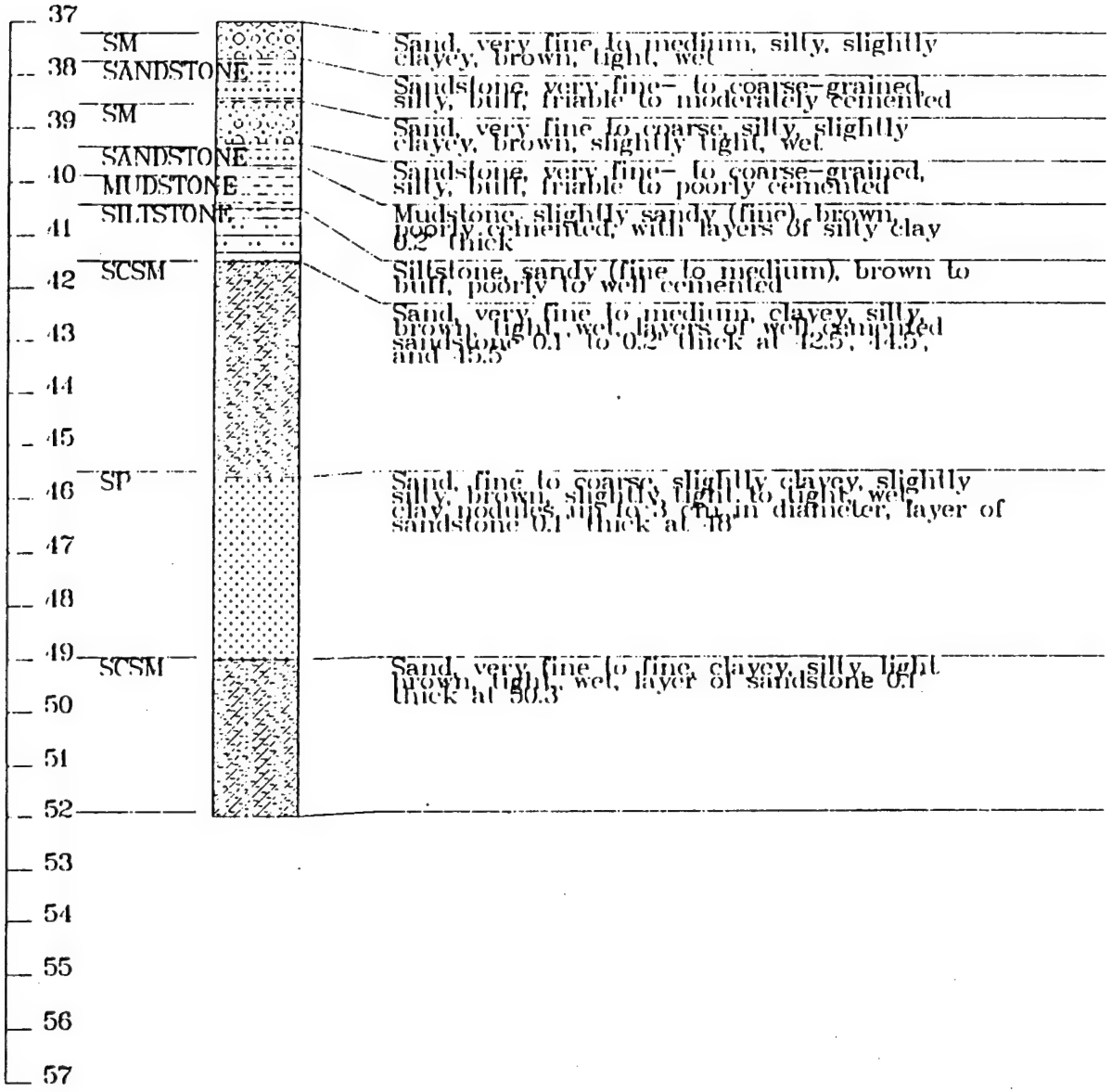
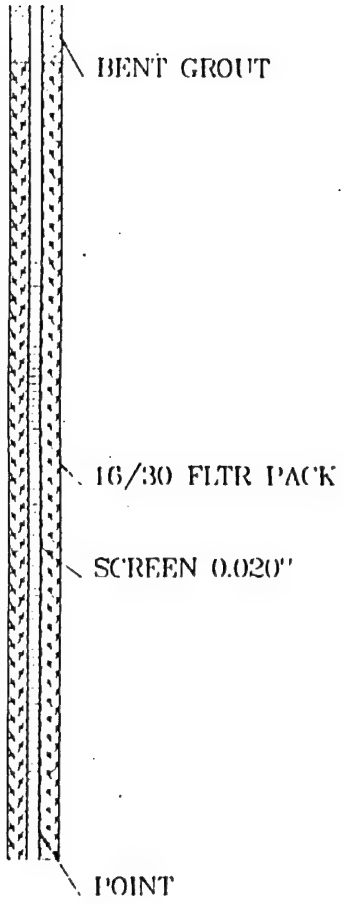
SM
SANDSTONE
SM
SCSM
SM
SANDSTONE
SM
SANDSTONE
OTHER
Sand, very fine to medium, silty, slightly clayey, brown, loose, wet, layers of sandstone 0.1' thick
Sandstone, very fine- to coarse-grained, silty, brown, poorly to moderately cemented, moist
Sand, very fine to medium, silty, slightly clayey, brown, slightly light, wet
Sand, very fine to medium, clayey, silty, brown, slightly light to loose, wet
Sand, very fine to medium, silty, brown, light, wet
Sandstone, very fine- to medium-grained, silty, brown to buff, poorly to moderately cemented, dry to moist, with layers of well cemented siltstone 0.2' thick
Sand, fine to coarse, silty, brown, loose, wet
Sandstone, fine- to coarse-grained, slightly silty, brown to buff, moderately to well cemented
Drilled with center bit, no core retrieved


CASING
BENT GROUT

WELL 210M1





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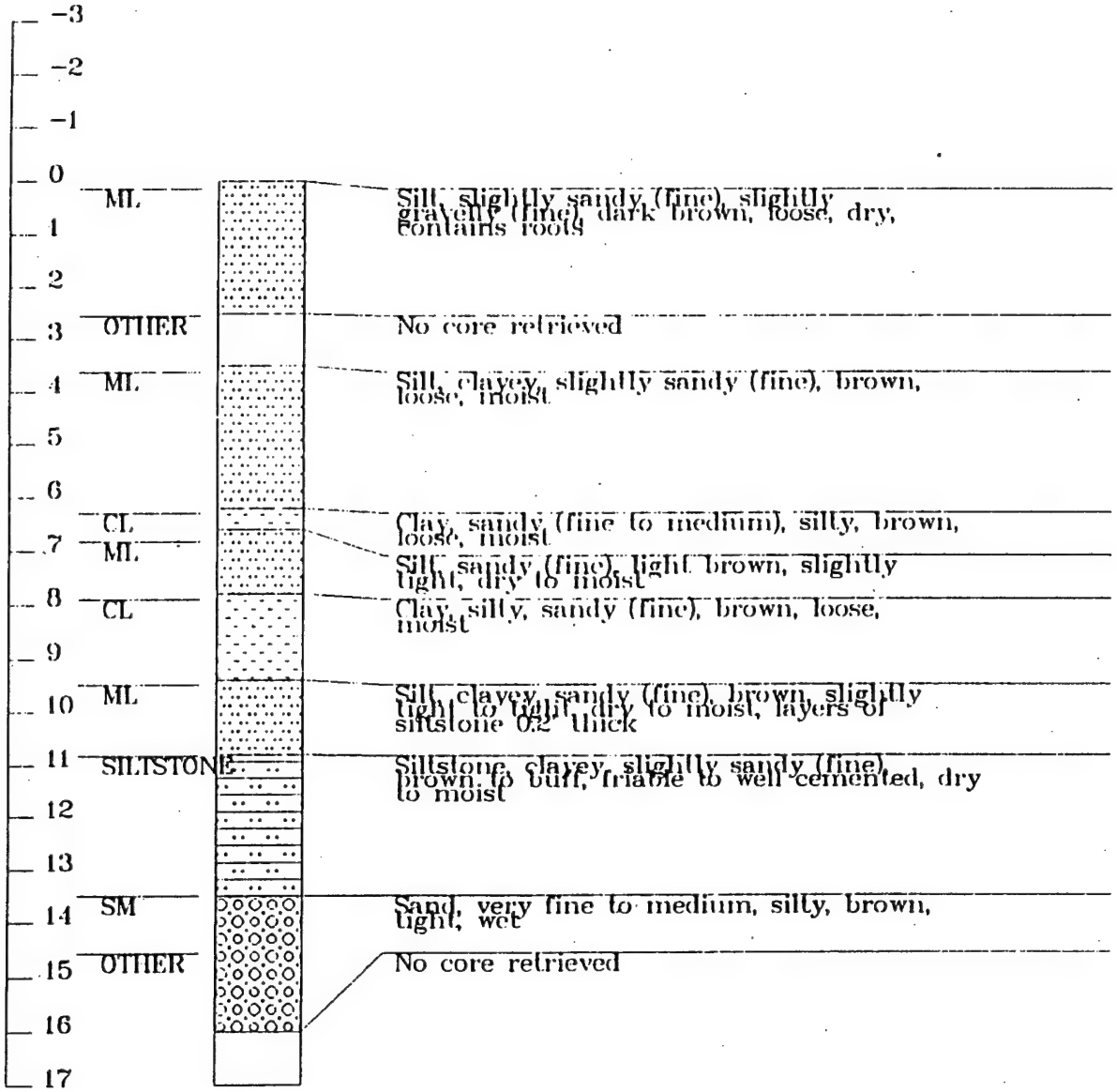
WELL 210D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ML
OTHER
ML
CL
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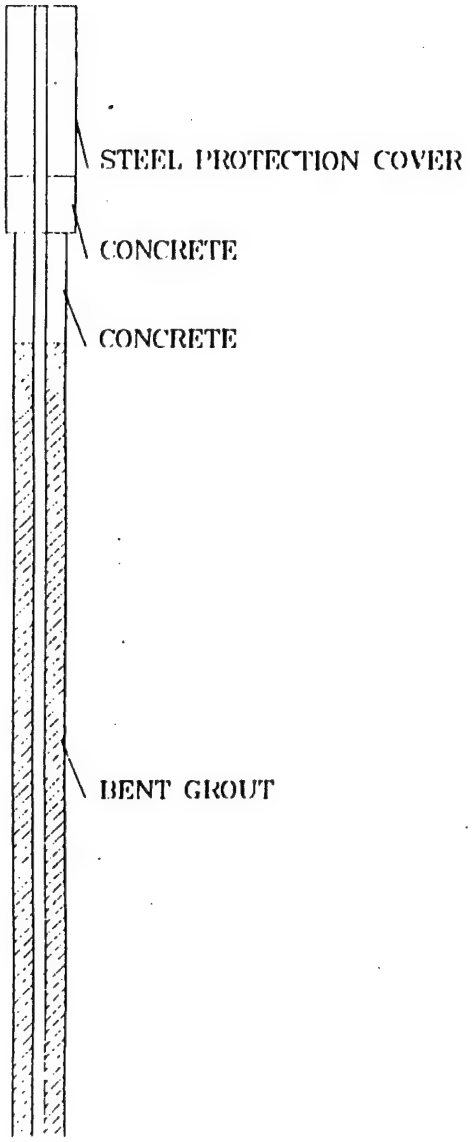
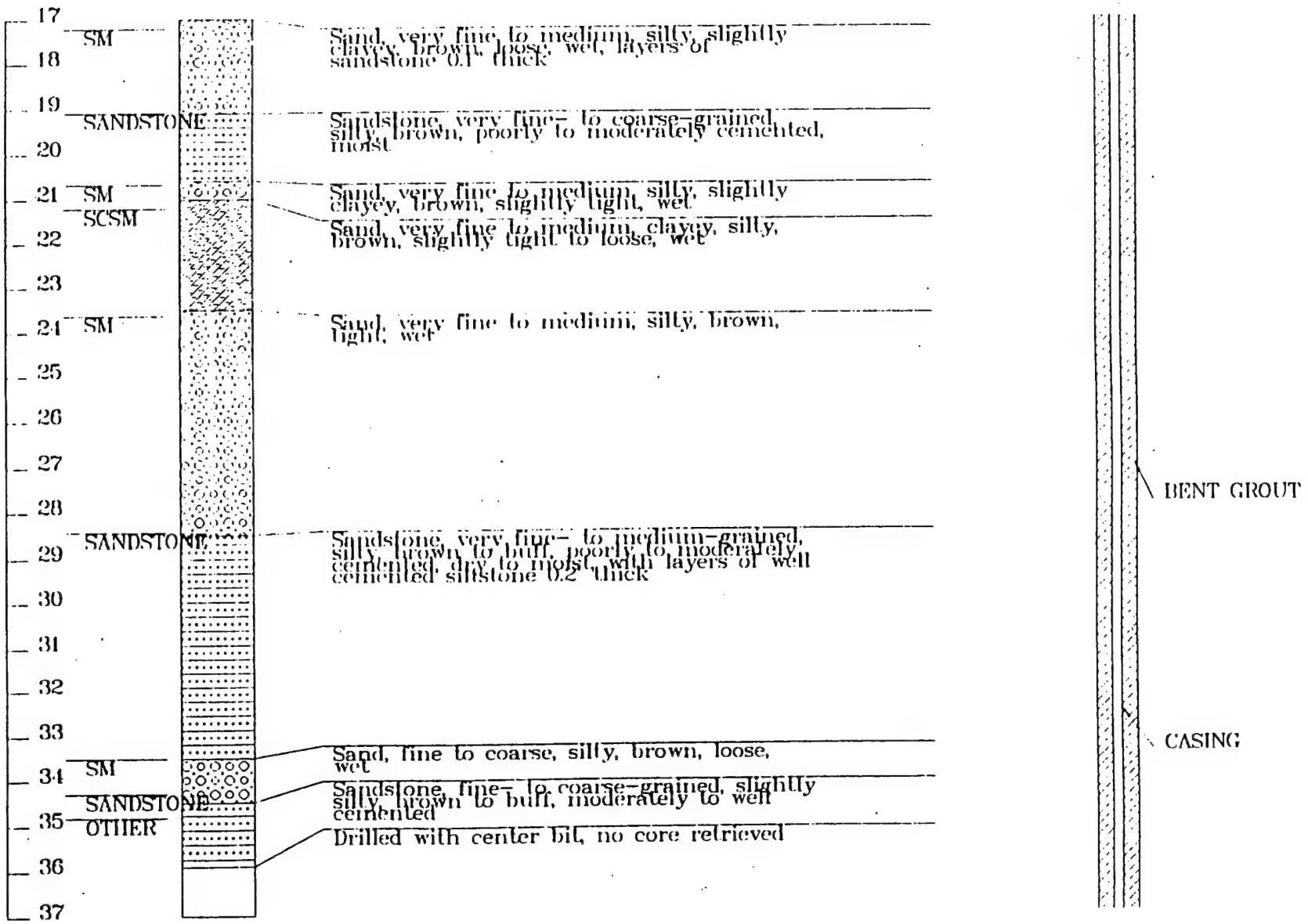
SILTSTONE
SM
OTHER
Silt, slightly sandy (fine), slightly gravelly (fine), dark brown, loose, dry, contains roots
No core retrieved
Silt, clayey, slightly sandy (fine), brown, loose, moist
Clay, sandy (fine to medium), silty, brown, loose, moist
Silt, sandy (fine), light brown, slightly light, dry to moist
Clay, silty, sandy (fine), brown, loose, moist
Silt, clayey, sandy (fine), brown, slightly light to light, dry to moist, layers of siltstone 0.2" thick
Siltstone, clayey, slightly sandy (fine), brown to buff, friable to well cemented, dry to moist
Sand, very fine to medium, silty, brown, light, wet
No core retrieved


STEEL PROTECTION COVER
CONCRETE
CONCRETE
BENT GROUT

WELL 210D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SM
SANDSTONE
SM
SCSM
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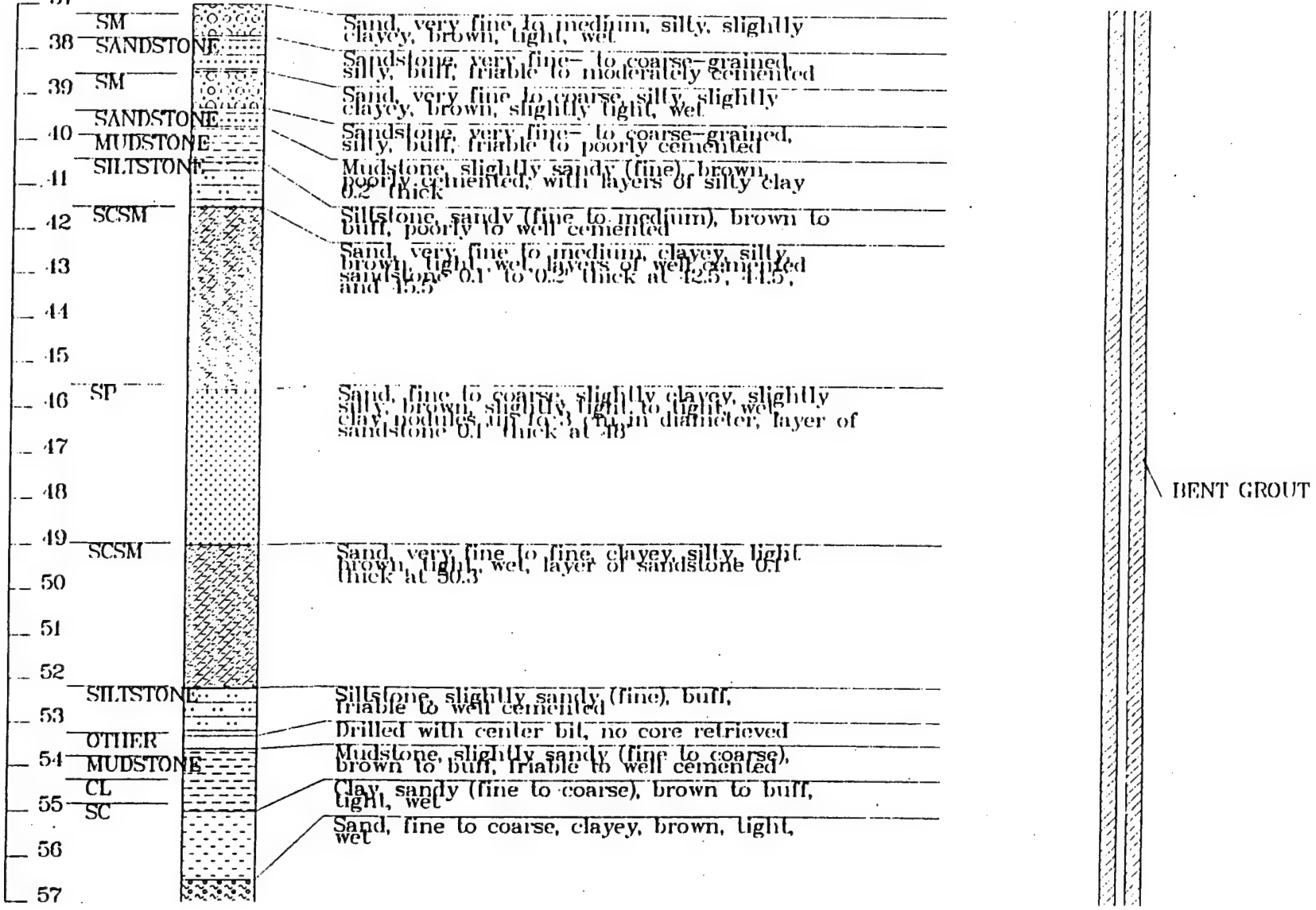
SANDSTONE
SM
SANDSTONE
OTHER
Sand, very fine to medium, silty, slightly clayey, brown, loose, wet, layers of sandstone 0.1" thick
Sandstone, very fine- to coarse-grained, silty, brown, poorly to moderately cemented, moist
Sand, very fine to medium, silty, slightly clayey, brown, slightly light, wet
Sand, very fine to medium, clayey, silty, brown, slightly tight to loose, wet
Sand, very fine to medium, silty, brown, light, wet
Sandstone, very fine- to medium-grained, silty, brown to buff, poorly to moderately cemented, dry to moist, with layers of well cemented siltstone 0.2" thick
Sand, fine to coarse, silty, brown, loose, wet
Sandstone, fine- to coarse-grained, slightly silty, brown to buff, moderately to well cemented
Drilled with center bit, no core retrieved
BENT GROUT
CASING

WELL 210D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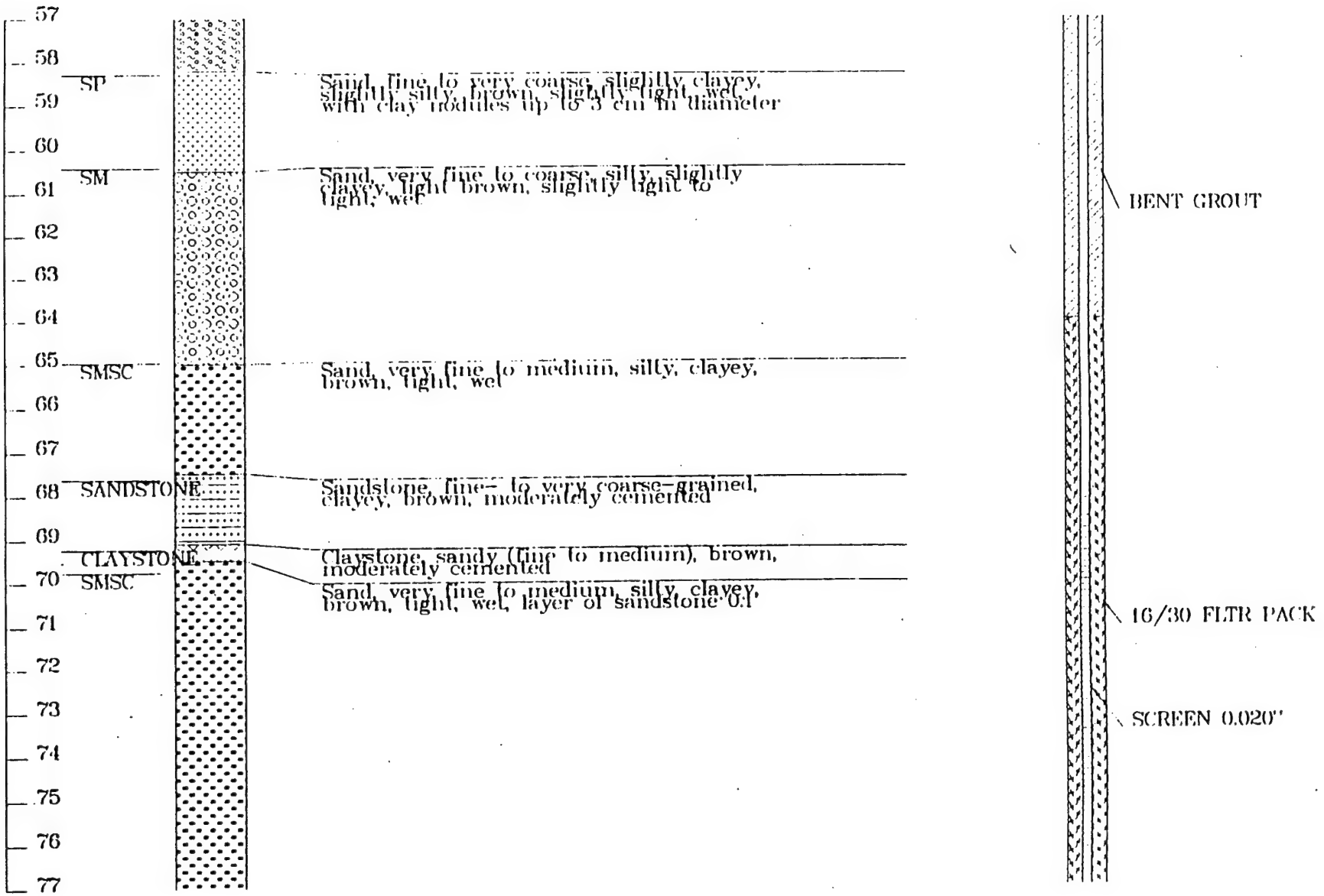
SM
SANDSTONE
SM
SANDSTONE
MUDSTONE
SILTSTONE
SCSM
SP
SCSM
SILTSTONE
OTHER
MUDSTONE
CL
SC
Sand, very fine to medium, silty, slightly clayey, brown, light, wet
Sandstone, very fine- to coarse-grained, silty, buff, friable to moderately cemented
Sand, very fine to coarse, silty, slightly clayey, brown, slightly light, wet
Sandstone, very fine- to coarse-grained, silty, buff, friable to poorly cemented
Mudstone, slightly sandy (fine), brown, poorly cemented, with layers of silty clay 0.2' thick
Siltstone, sandy (fine to medium), brown to buff, poorly to well cemented
Sand, very fine to medium, clayey, silty, brown, light, wet, layers of well cemented sandstone 0.1' to 0.2' thick at 42.5', 44.5', and 45.5'
Sand, fine to coarse, slightly clayey, slightly silty, brown, slightly light to light, wet, clay nodules up to 3" in diameter, layer of sandstone 0.1' thick at 48'
Sand, very fine to fine, clayey, silty, light brown, light, wet, layer of sandstone 0.1' thick at 50.3'
Siltstone, slightly sandy (fine), buff, friable to well cemented
Drilled with center bit, no core retrieved
Mudstone, slightly sandy (fine to coarse), brown to buff, friable to well cemented
Clay, sandy (fine to coarse), brown to buff, light, wet
Sand, fine to coarse, clayey, brown, light, wet
BENT GROUT

WELL 210D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SP
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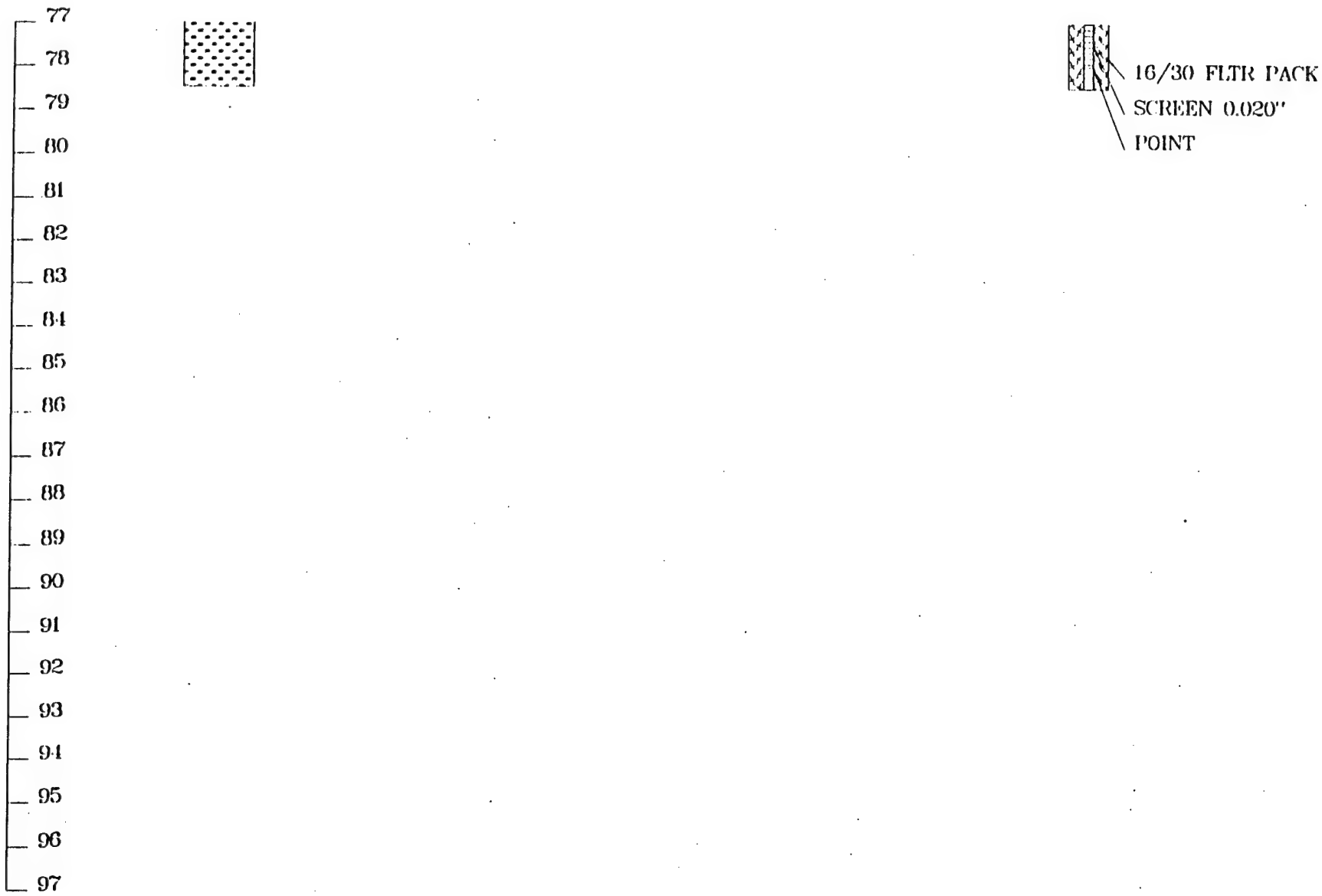
SMSC
SANDSTONE
CLAYSTONE
SMSC
Sand, fine to very coarse, slightly clayey, slightly silty, brown, slightly light, wet, with clay nodules up to 3 cm in diameter
Sand, very fine to coarse, silty, slightly clayey, light brown, slightly light to light, wet
Sand, very fine to medium, silty, clayey, brown, light, wet
Sandstone, fine- to very coarse-grained, clayey, brown, moderately cemented
Claystone, sandy (fine to medium), brown, moderately cemented
Sand, very fine to medium, silty, clayey, brown, light, wet, layer of sandstone 0.1'
BENT GROUT
16/30 FLTR PACK
SCREEN 0.020"

WELL 210D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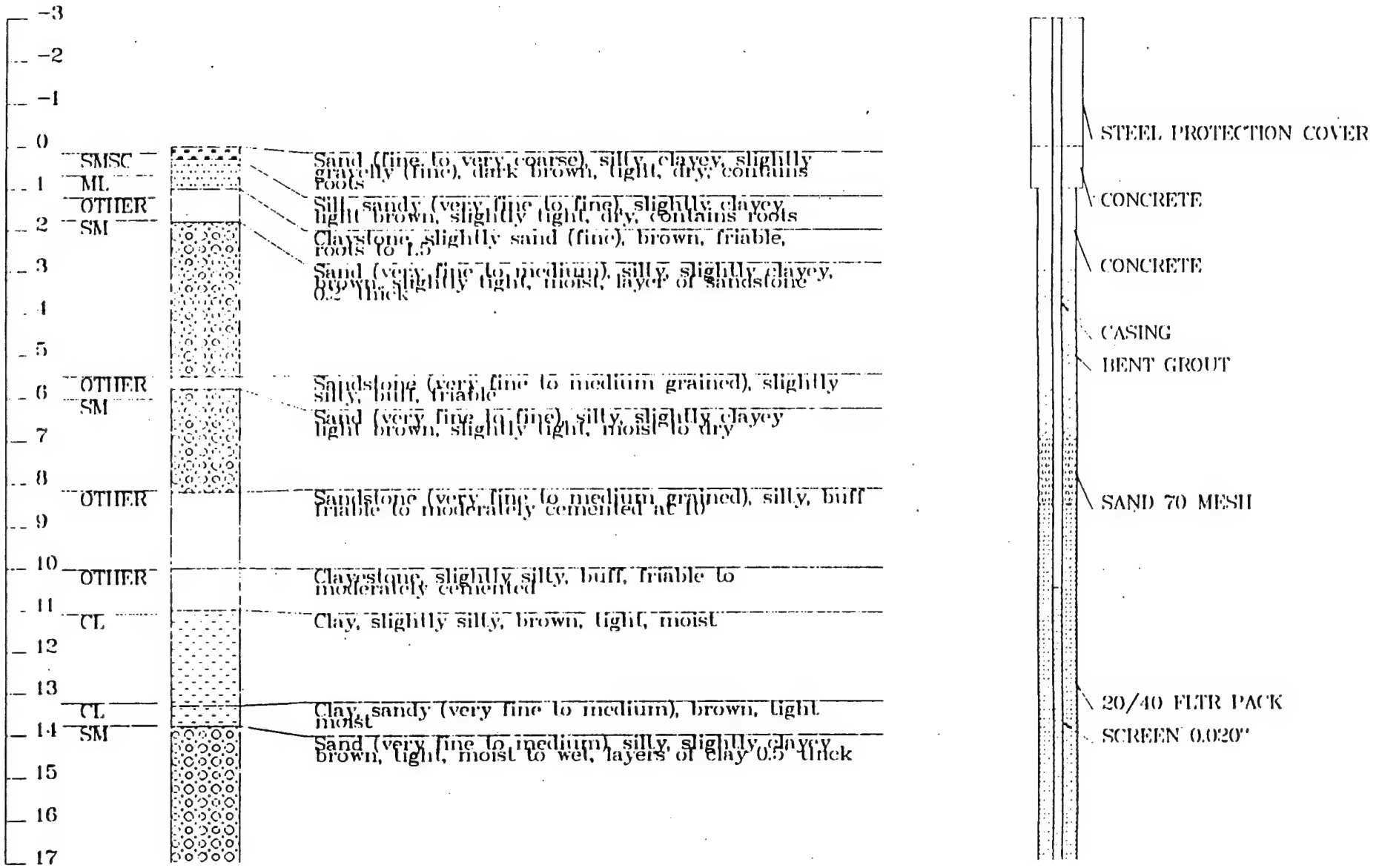
16/30 FLTR PACK
SCREEN 0.020"
POINT

WELL 239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SMSC
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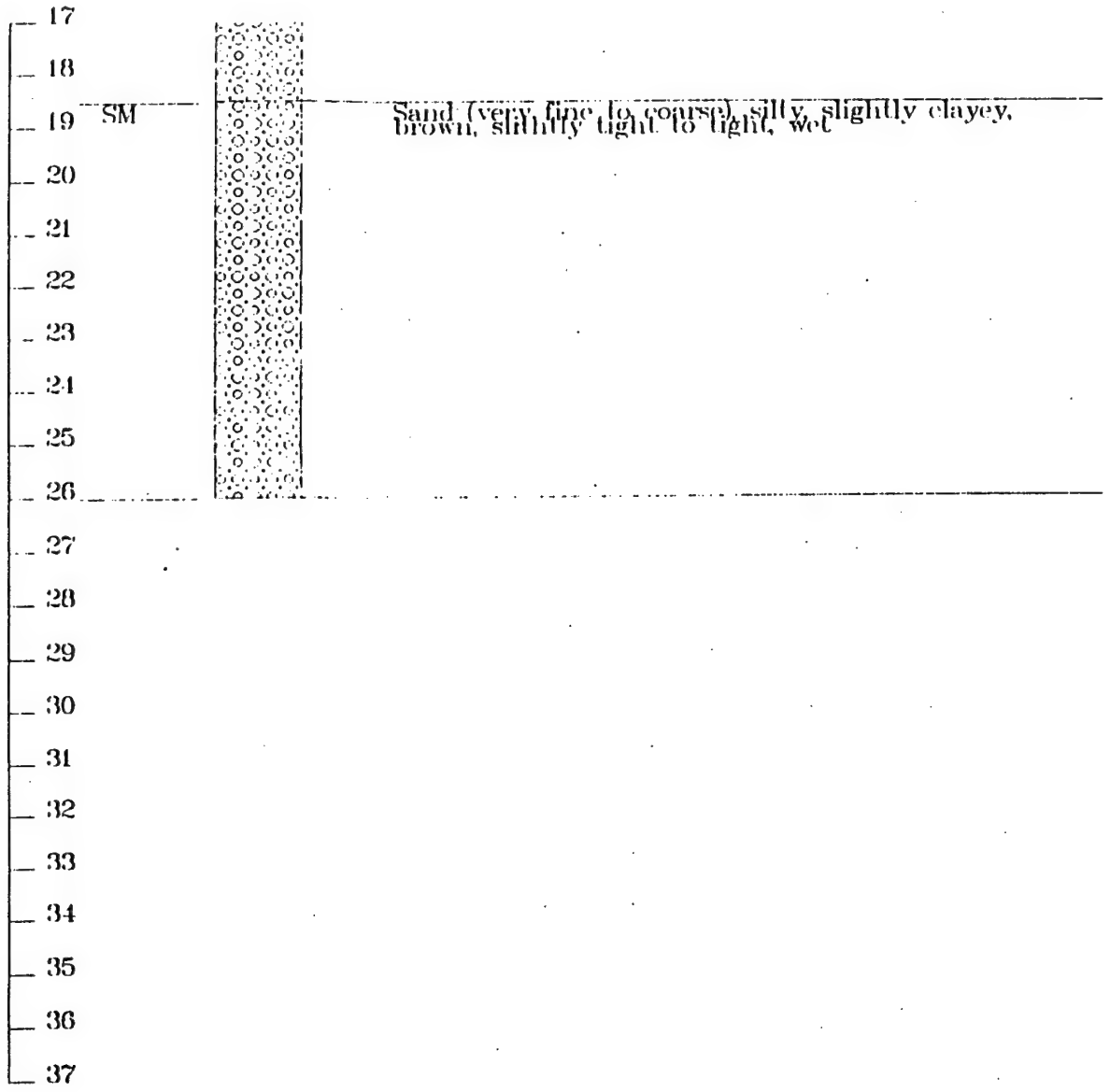
OTHER
CL
CL
SM
Sand (fine to very coarse), silty, clayey, slightly gravelly (fine), dark brown, light, dry, contains roots
Silt, sandy (very fine to fine), slightly clayey light brown, slightly light, dry, contains roots
Claystone, slightly sand (fine), brown, friable, roots to 1.5
Sand (very fine to medium), silty, slightly clayey, brown, slightly light, moist, layer of sandstone 0.2 thick
Sandstone (very fine to medium grained), slightly silty, buff, friable
Sand (very fine to fine), silty, slightly clayey light brown, slightly light, moist to dry
Sandstone (very fine to medium grained), silty, buff friable to moderately cemented at 10
Claystone, slightly silty, buff, friable to moderately cemented
Clay, slightly silty, brown, light, moist
Clay, sandy (very fine to medium), brown, light moist
Sand (very fine to medium), silty, slightly clayey brown, light, moist to wet, layers of clay 0.5 thick
STEEL PROTECTION COVER
CONCRETE
CONCRETE
CASING
BENT GROUT
SAND 70 MESH
20/40 FLTR PACK
SCREEN 0.020"

WELL 239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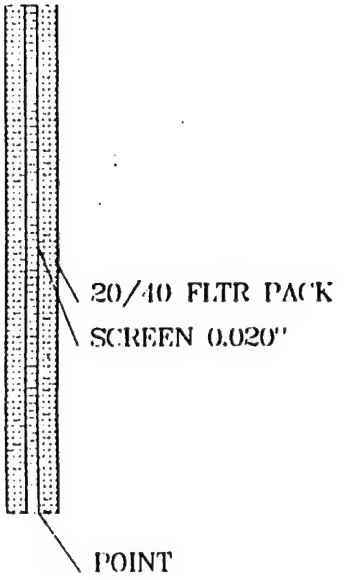
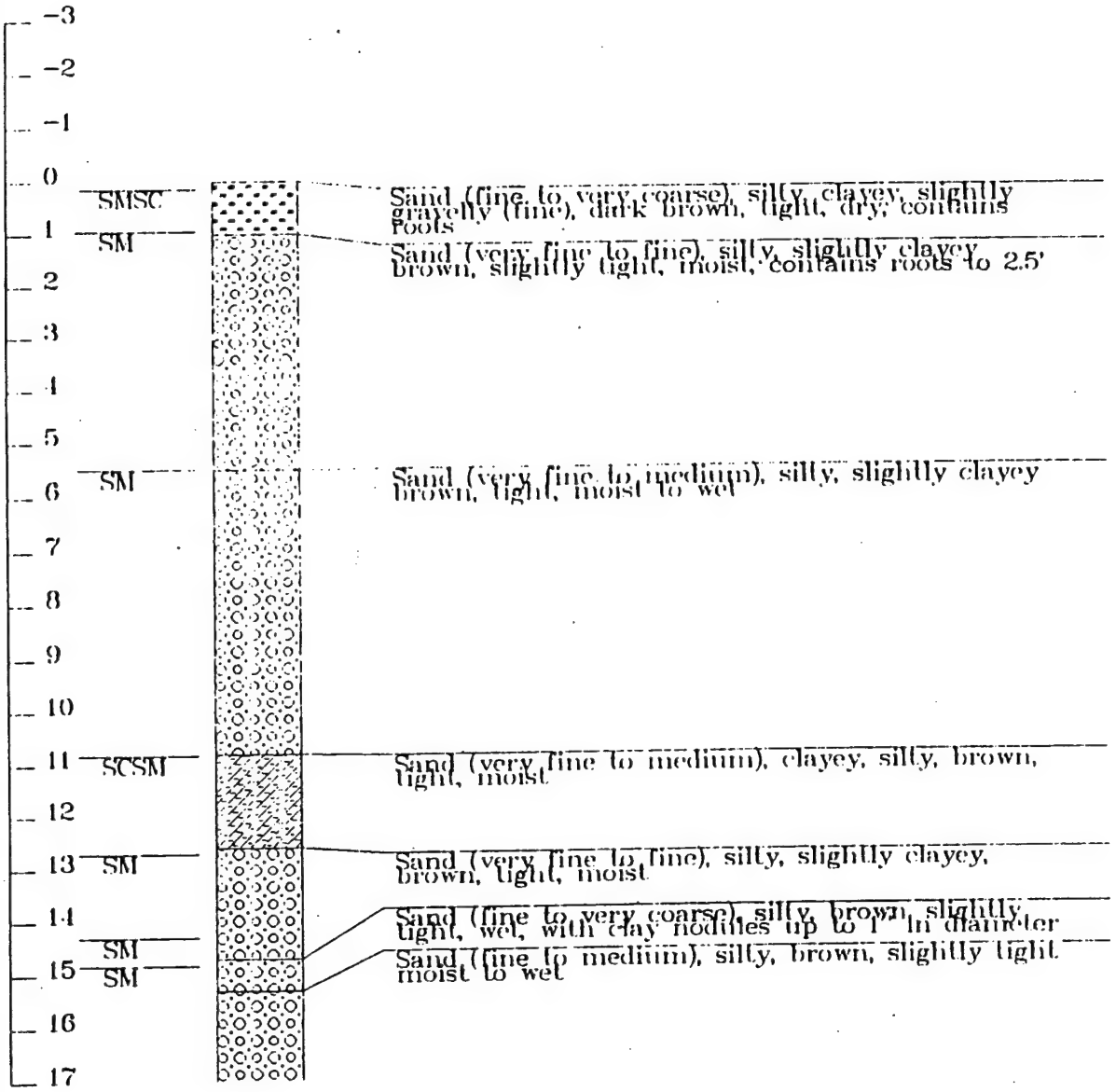
SM
Sand (very fine to coarse), silty, slightly clayey, brown, slightly tight to tight, wet


20/40 FLTR PACK
SCREEN 0.020"
POINT

WELL 240R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SMSC
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SCSM
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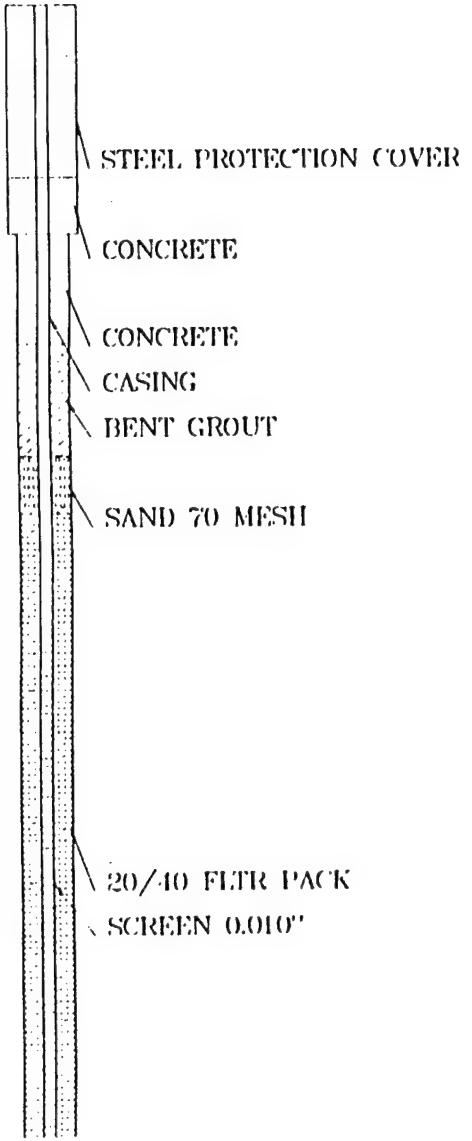
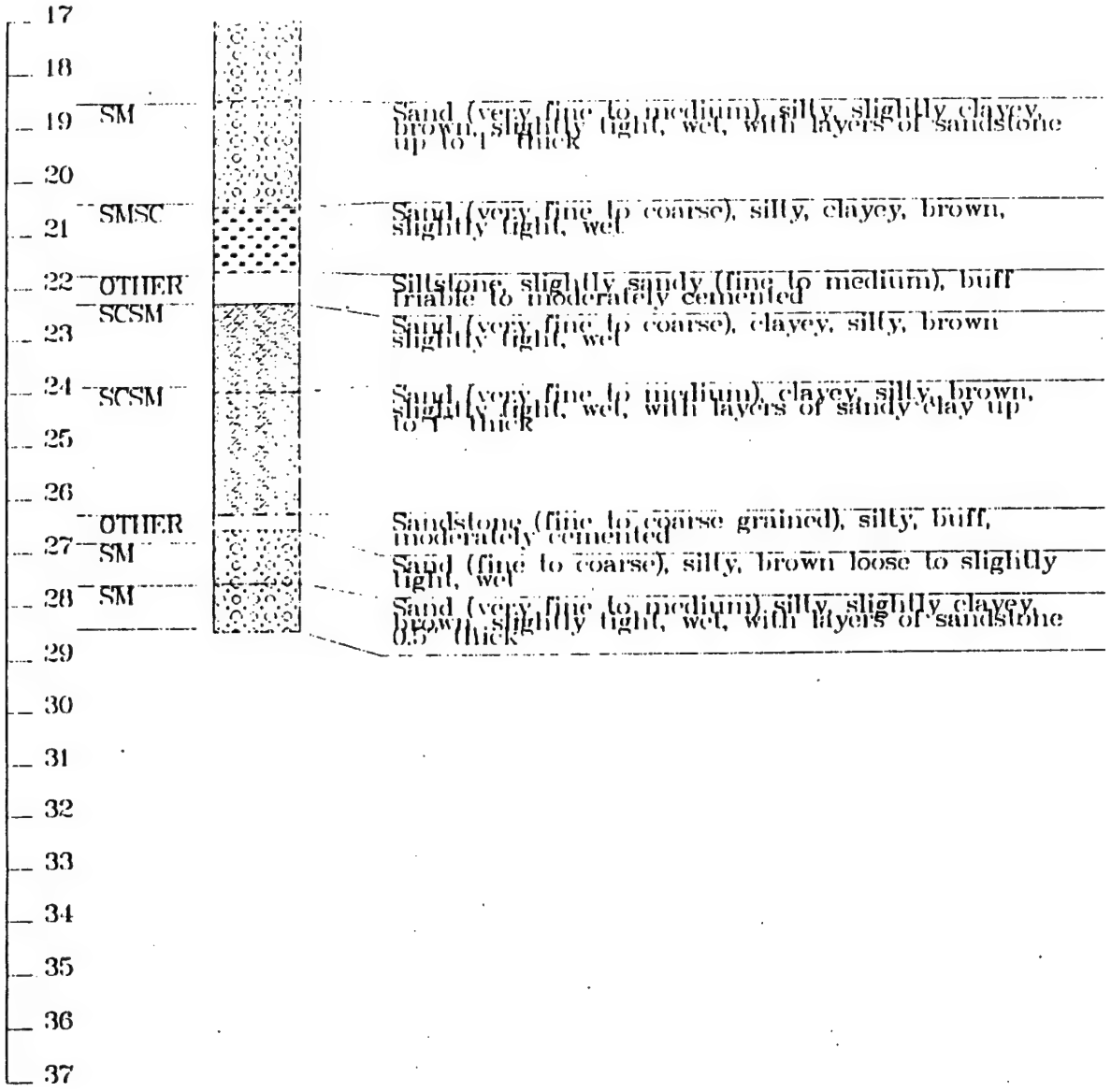
SM
SM
Sand (fine to very coarse), silty, clayey, slightly gravelly (fine), dark brown, light, dry, contains roots
Sand (very fine to fine), silty, slightly clayey, brown, slightly light, moist, contains roots to 2.5'
Sand (very fine to medium), silty, slightly clayey brown, light, moist to wet
Sand (very fine to medium), clayey, silty, brown, light, moist
Sand (very fine to fine), silty, slightly clayey, brown, light, moist
Sand (fine to very coarse), silty, brown, slightly light, wet, with clay nodules up to 1" in diameter
Sand (fine to medium), silty, brown, slightly light moist to wet


STEEL PROTECTION COVER
CONCRETE
CONCRETE
CASING
BENT GROUT
SAND 70 MESH
20/40 FLTR PACK
SCREEN 0.010"

WELL 240R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SCSM
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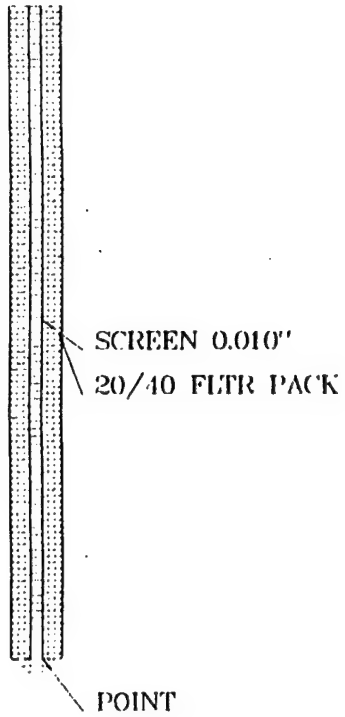
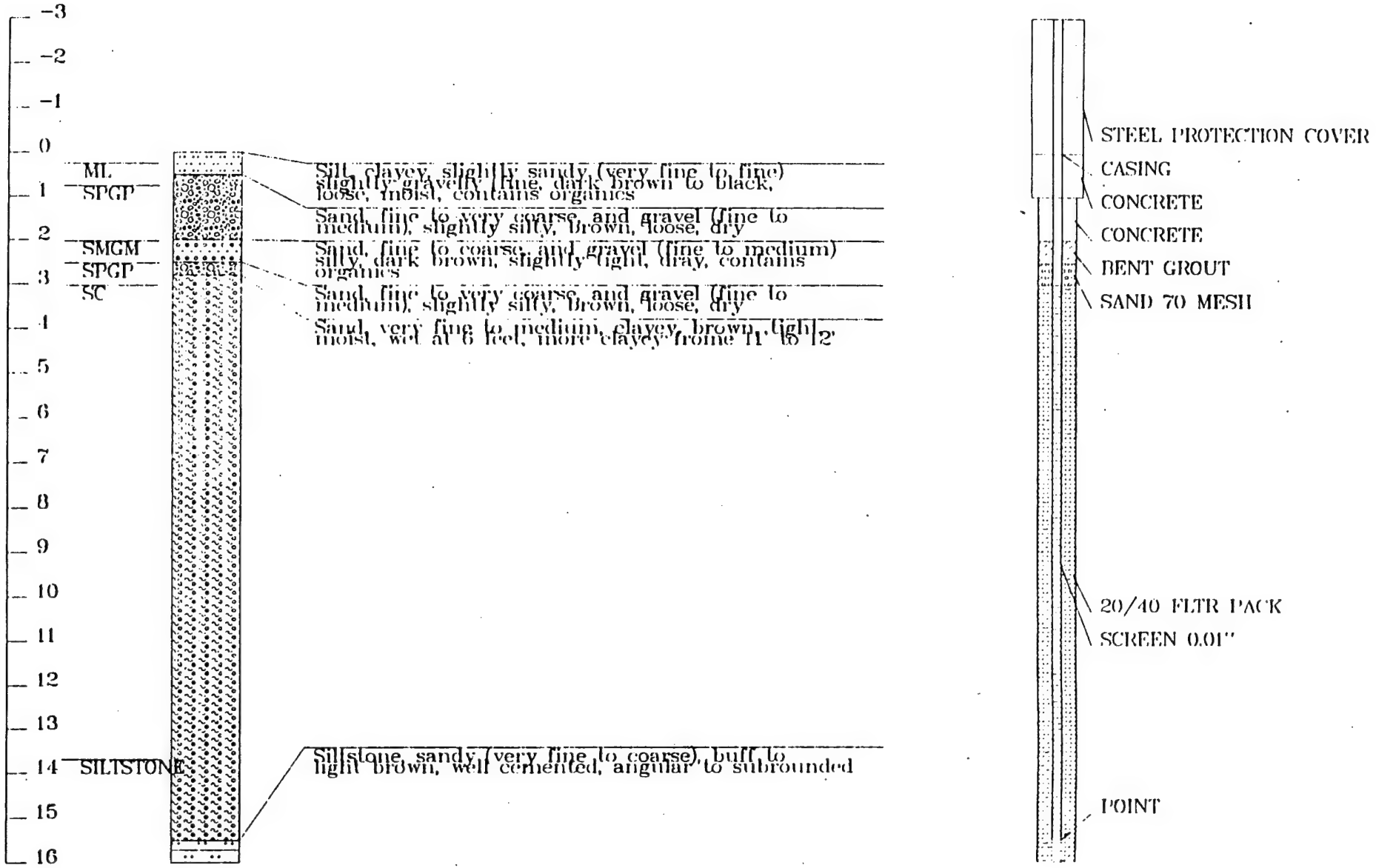
SM
Sand (very fine to medium), silty, slightly clayey, brown, slightly tight, wet, with layers of sandstone up to 1" thick
Sand (very fine to coarse), silty, clayey, brown, slightly tight, wet
Siltstone, slightly sandy (fine to medium), buff friable to moderately cemented
Sand (very fine to coarse), clayey, silty, brown slightly tight, wet
Sand (very fine to medium), clayey, silty, brown, slightly tight, wet, with layers of sandy clay up to 1" thick
Sandstone (fine to coarse grained), silty, buff, moderately cemented
Sand (fine to coarse), silty, brown loose to slightly tight, wet
Sand (very fine to medium), silty, slightly clayey, brown, slightly tight, wet, with layers of sandstone 0.5" thick


SCREEN 0.010"
20/40 FLTR PACK
POINT

WELL 241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SC
SILTSTONE
Silt, clayey, slightly sandy (very fine to fine) slightly gravelly (fine, dark brown to black, loose, moist, contains organics
Sand, fine to very coarse, and gravel (fine to medium), slightly silty, brown, loose, dry
Sand, fine to coarse, and gravel (fine to medium) silty, dark brown, slightly light, dray, contains organics
Sand, fine to very coarse, and gravel (fine to medium), slightly silty, brown, loose, dry
Sand, very fine to medium, clayey, brown, high moist, wet at 6 feet, more clayey from 11' to 12'
Siltstone, sandy (very fine to coarse), buff to light brown, well cemented, angular to subrounded
STEEL PROTECTION COVER
CASING
CONCRETE
CONCRETE
BENT GROUT
SAND 70 MESH
20/40 FLTR PACK
SCREEN 0.01"
POINT

APPENDIX B

GEOLOGIC BOREHOLE LOGS, WELL CONSTRUCTION DIAGRAMS, MONITORING WELL DEVELOPMENT AND GROUNDWATER SAMPLING RECORDS, SLUG TEST ANALYSES, AND SURVEY DATA

GEOLOGIC BORING LOG

JOB NUMBER: 722450.30010 | CLIENT: F.E. Warren AFB | DATE: 4-29-97
BORING NUMBER: PES 1S | BORING DIA.: 8.25" OD 4.25" ID | ELEVATION:
RIG TYPE: | CONTRACTOR: Drilling Engineers | DATUM: N.G.C.
TEMPERATURE (°F): 40°F | WEATHER: Raining, very windy | GEOLOGIST: M. Reimann, J. Biddle
DRLG MED: N/A
COMMENTS:

Depth (ft.)	Pro-file	USCS	Geologic Description	Split Spoon Interval	Laboratory Sample Identification	Sample Type	PID ppmv	Remarks
1			0-1 - Topsoil, Dark Brown, Wet Roots, soft	0-5			2.3 @ 2.0	Start Drilling @ 14:00
				0-4.5			2.6 @ 2.5'	Background = 2.6
			1-2 Clay, Wet, Med brown some sand, stiff, Firm					
5								
			2-3 - silty sand, stiff, firm slightly plastic, some med. pebble gravel wet.					
10								
			3-4 - Top Soil Firm, Damp. Stiff, DARK BROWN.					
15			4-4.5 - No Recovery					
			4.5-7.5 - Siltstone, Firm, Med stiff, slightly plastic Dry	4.5 ↓ 9.5			2.6 @ 5.0'	
20			7.5-8 - conglomerate, Sandy med pebble gravel, soft. Loose, Dry.				1.6 @ 7.5	← background LC
25			8-9.5 No Recovery				1.8	10'
			9.5-10.5 - Sandstone, silty Damp, Light brown, soft, Firm	9.5 ↓ 14.5			2.1	@ 12.5'
30			10.5-12.5 - Claystone, stiff, Firm, Damp, Med brown, slightly plastic.					
			12.5-14.5: No Recovery.	14.5 ↓ 19.5			1.8	@ 15'
35			14.5-17 - SAA				1.8	@ 17.5'
			17-18.5 - Clay Stone, silty Damp, Very Stiff, Firm, med, brown.					
40			19.5-22.5 - SAA.	19.5 ↓ 22.5				
45								

NOTES:
PID - Photoionization Detector
ppmv - Parts per Million, Volume per Volume
BGS - Below Ground Surface
TOC - Top of Casing
na - Not Analyzed
HS - Sample Headspace
SS - Split Spoon Sample
G - Grab Sample

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GEOLOGIC BORING LOG

JOB NUMBER: 722450.30010
BORING NUMBER: PBS 15
RIG TYPE:
TEMPERATURE (°F): 40°F
CLIENT: F.E. Warren AFB
BORING DIA.:
CONTRACTOR: Drilling Engineers
WEATHER: Rainy - Very windy
DRLG MED: N/A
DATE: 4-29-99
ELEVATION:
DATUM:
GEOLOGIST: M. Reimann, T. Bidgood

COMMENTS:

Depth (ft.)	Pro-file	USCS	Geologic Description	Split Spoon Interval	Laboratory Sample Identification	Sample Type	PID ppmv	Remarks
1			22.5 - 24.5, claystone, SAA	22.5 - 24.5				
5			24.5 - 27.0 - SAA	24.5 - 27.0			1.6	@25'
			27 - 29.27 - SAA.	27 - 29			Incr	27.5
10			29 - 32 SAA.	29 - 32			1.8	@30' - background 1.6/1.8
			32 - 32.5 Silt	30 - 34.			1.6	@34.5 Water @ ~ 32.5' bgs.
15			32.5 - 34 - SANDSTONE Fine to med grain. med. St. A, Firm, Wet. light to med brown.					- Stopped here on 4/29
20			34 - 36.5 - Fine to med grn Sandstone, silty, Firm Stiff, Slightly Plastic, light brown, wet.	34 - 36.5				
25			36.5 - 38 - Sandstone SAA	36.5 - 37				
			38 - 38.5 - ~~Concrete~~ med. to coarse grn Sand Stn Interbedded, wet light brown Firm, mod St. ?.					
30			~~38.5~~ 38.5 - 39 - No Rec.					- Finished 4/30
35								
40								
45								

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SS - Split Spoon Sample
G - Grab Sample

GEOLOGIC BORING LOG

JOB NUMBER: 722450.30010 CLIENT: F.E. Warren AFB DATE: 4-28-29-99
BORING NUMBER: PE52D BORING DIA.: 8.25 ELEVATION:
RIG TYPE: CONTRACTOR: DRILLING ENGINEERS DATUM: TOC
TEMPERATURE (°F): ~55°F WEATHER: Windy, Cloudy GEOLOGIST: M. Reimann, J. Bidgood
DRLG MED: N/A
COMMENTS:

Depth (ft.)	Pro-file	USCS	Geologic Description	Split Spoon Interval	Laboratory Sample Identification	Sample Type	PID ppmv	Remarks
1			0-1.5 Topsoil, DARK BROWN Moist Roots.					
			1.5-3.0 - Silt, Sandy med brown, moist Slightly plastic, med Stiff firm.			2.5'	=2.8	ppmv
5						5.'	= 2.8	
						7.5'	= 2.8	
			3-3.5 Sand, silty DAMP, nonplastic med stiff, Firm.			10'	= 2.9	
10						12.5	= 2.8	
			3.5-5- no Recovery			17.5	2.8	
15			5-7.5 Sand, silty brown, DAMP, Fine to med grain Sand, nonplastic Silt Firm.					
			7.5-8 Sand Stone, soft. Firm, DAMP, silty			20'	= 2.9	
20								
						22.5	= 2.9	
			8-9.5 no Recovery			25'	= 2.8	
25								
			9.5-11.5 conglomerate pebble to cobble size gravel mixed w/ fine to coarse gr. Sand DAMP. poorly sorted well graded, medium stiff, firm			27.5	= 3.0	
30						30'	= 3.0	
			non plastic, light Brown					
			11.5-12.5 conglomerate Cobble size, silty fine Sand matrix, very stiff Dense, non plastic, DAMP. Light brown					
35								
			12.5-14.5 no Recovery.					
40								
			14.5-16. SAA ~~conglomerate~~ pebble to cobble size gravel mixed w/ fine to coarse gr. Sand, DAMP., poorly sorted well graded, light brown					
45								

Background = 2.8 ppm

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GEOLOGIC BORING LOG

JOB NUMBER:	722450.30010	CLIENT:	F.E. Warren AFB	DATE:	4-28
BORING NUMBER:	PES ~~[illegible]~~ 2D	BORING DIA.:	8.25 OD	ELEVATION:	
RIG TYPE:		CONTRACTOR:	Drilling Engineers	DATUM:	TOC
TEMPERATURE (°F):	45	WEATHER:	windy, cloudy	GEOLOGIST:	M. Reimann, J. Bidgood
		DRLG MED:	n/a		
COMMENTS:					

Depth (ft.)	Pro-file	USCS	Geologic Description	Split Spoon Interval	Laboratory Sample Identification	Sample Type	PID ppmv	Remarks
1								
			16.5-17.5 - Claystone w/silt ~~to~~ med. stiff plastic, Firm, light Brown DAMP.					
5								
			17.5-18.5 Siltstone med, brown, very stiff brittle, Firm					
10								
			18.5-19.5 no Recovery.					
			19.5-20.5 - Claystone med brown, DAMP, plastic. stiff, Firm.					
15								
			20.5-21.5 - Fine grain Sand stone, silty, very stiff. Dense, light brown. DAMP.					Water table Appears to be at ~24 ft bgs
20								
			21.5-24.5 - Fine grain Sand stone, very stiff Dense, med brown, non Plastic, moist					
25								
			24.5-26.5 - Sandstone light brown DAMP nonplastic med stiff Dense					
30								
			26.5-26.75 - Claystone silty.					
			26.75-27.5 Siltstone some sand, Friable Gray, DRY, very stiff Dense, non plastic.					
35								
			27.5-28.5 - Claystone, some silty DAMP, Med brown, HARD ~~to~~ Firm.					
40								
			28.5-29.5 - Siltstone some sand. nonplastic, stiff, Firm, DAMP					
45								

Background = 28 ppmv

NOTES:

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GEOLOGIC BORING LOG

JOB NUMBER:	722450.30010	CLIENT:	F.E. Warren AFB	DATE:	4-29-99
BORING NUMBER:	PES ~~40~~ 22	BORING DIA.:	8.25 OD 4.25 ID	ELEVATION:	
RIG TYPE:		CONTRACTOR:	Drilling Engineers	DATUM:	TOC
TEMPERATURE (°F):	40°F	WEATHER:	Foggy, Breezy	GEOLOGIST:	M. Reimann, J. Bidgood
		DRLG MED:	N/A		
COMMENTS:					

Depth (ft.)	Pro-file	USCS	43.5 Geologic Description	Split Spoon Interval	Laboratory Sample Identification	Sample Type	PID ppmv	Remarks
1			~~39.5-44.5 - Sandstone, silty fine to med grain sandstone, wet, Lt. Brown, slightly plastic, stiff, firm.~~					
5			~~43.5-44.5 = No Recovery.~~					
			~~44.5-49.5 = No Recovery~~					
10			29.5-32.5 - Fine to med grain sandstone, some silt, nonplastic light Brown/Gray, very stiff Dense					
15			32.5-33.5 - siltstone, nonplastic Gray/Lt. Brown, HARD, Dense					
			33.5-34.5 no recovery					
20			34.5-39.5 no recovery					
			39.5-43.5 sandstone, silty Fine to med grain sandstone wet, Lt. Brown, slightly plastic, stiff, firm					
25			43.5-44.5 No Rec.					
30			44.5-49.5 No Rec					
35								
40								
45								

NOTES:

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Sheet 1 of 2

GEOLOGIC BORING LOG

JOB NUMBER: 722450.30010 CLIENT: F.E. Warren AFB DATE: 5/4/95
BORING NUMBER: PES 3D BORING DIA.: 8.25" OD 4.25" ID ELEVATION:
RIG TYPE: CONTRACTOR: Drilling Engineers DATUM: TOC
TEMPERATURE (°F): 30° WEATHER: Clear, Windy GEOLOGIST: J. BIDGOOD
DRLG MED: N/A
COMMENTS:

Depth (ft.)	Profile	USCS	Geologic Description	Split Spoon Interval	Laboratory Sample Identification	Sample Type	PID ppmv	Remarks
1			0-0.5 - TOPSOIL, DARK BROWN ROOTS, moist, Roots	0	2.5'	—	2.2/2.5	PID in soil / PID background
				–	5.0'	—	3.0/1.5	
5			0.5-1.5 - Clay, Fine, stiff dk K brown, Damp ~~Some~~ little pebble gravel	4.5	7.5	—	2.2/2.2	
					11'	—	2.5/2.5	
10			1.5-3.0 - Sand, Fine grain to med. grain, little silt, stiff, compacted in spoon, moist,	3.1	15'	–	3.3/2.5	← Soil Sample For Analysis. TCE/BTEX/TOC.
15			3-4.5 - NO Recovery		20'	–	2.2/2.2	
			4.5-6.5 - ~~Siltstone, very Sandy, Fine~~ Sandstone, Fine grain, very silty, red Brown, moist, Stiff Firm, Sl. plastic	4.5 – 9.5	22.5	—	2.2/2.2	
20								
			6.5-7.5 - Sandstone, Fine grain, very silty, red Brown moist ~~silt stone~~, Stiff Firm, Sl. plastic		26	—	2.2/2.2	
25								
			7.5-8.5 - Sandstone, Fine to med grain, some Silt, stiff, Firm, moist med brown		28.5	–	2.2/2.2	
30							~~3.3/2.5~~	
			8.5-9.5 No Rec					
			9.5 - ~~Thin~~ Red Sandstone Fine to coarse grain Sand, med to coarse pebble gravel, very wet ~~was~~ Soft, Firm, med brown	9.5 – 14.5				
35								
40			~~Red~~ 12-13 - Siltstone gray, ~~Dry~~ Damp, ~~Brittle~~ Soft, Dense, gray color					
45			13-14.5 NO Rec.					

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SS - Split Spoon Sample
G - Grab Sample

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GEOLOGIC BORING LOG

JOB NUMBER:	722450.30010	CLIENT:	F.E. Warren AFB	DATE:	5-4-98
BORING NUMBER:	PBS 3D	BORING DIA.:	8.25 OD 4.25 ID	ELEVATION:	
RIG TYPE:		CONTRACTOR:	Drilling Engineers	DATUM:	
TEMPERATURE (°F):	50	WEATHER:	50° clear, windy	GEOLOGIST:	S. Bidlack
		DRLG MED:	N/A		

COMMENTS:

Depth (ft.)	Pro-file	USCS	Geologic Description	Split Spoon Interval	Laboratory Sample Identification	Sample Type	PID ppmv	Remarks
1			14.5 – 16.5 – Siltstone wet, stiff, Firm. Bedded layers (Brittle) gray,	14.5 – 19.5				WATER TABLE @ ~ 15' bgs.
5			16.5 – 17, clay Stone. Damp, stiff, Firm.					
10			17 – 18.5 – Sandstone very Fine grane, silty wet, mill plastic stiff, firm					
15			18.5 – 19.5 NO REC.					
20			19.5 – 24.5 Sandstone, very Fine grain, silty st. plastic, wet / Firm, stiff med Brown. layer of clay stone at 22' – 0.1' thick	19.5 – 24.5				
25			24.5 – 26 – Clay Stone, wheathered w/ siltstone, little Fine grain, Sandy, Firm, stiff, Wet, mild, Brown, sl. plastic	24.5 – 29.5				
30			26 – 28.5 Sandstone, Fine grain, silty, Firm stiff, wet, sl. plastic					
35			28.5 – 29.5, NO Recov.					
40			29.5 – 32 – Fine Grain Sandstone, silty, Firm, stiff med brown, very wet, sl. plastic,	29.5 – 34.5				
45			32 – 34.5 – NO Rec					
			34.5 – 37.0 Sandstone Fine grain silty, Wet med brown, Firm stiff, sl. plastic. 37-39 – Sandstone, Fine grain, silty Very stiff, Firm, wet.					Screen from 34.5 – 39.5

NOTES:

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GEOLOGIC BORING LOG

JOB NUMBER:	722450.30010	CLIENT:	F.E. Warren AFB	DATE:	4-27-99
BORING NUMBER:	PEG 40	BORING DIA.:	8.25"	ELEVATION:	
RIG TYPE:		CONTRACTOR:	Drilling Engineers	DATUM:	TOC
TEMPERATURE (°F):	52° F	WEATHER:	RAIN	GEOLOGIST:	M. Remson
		DRLG MED:	N/A		
COMMENTS:					

Depth (ft.)	Profile	USCS	Geologic Description	Split Spoon Interval	Laboratory Sample Identification	Sample Type	PID ppmv	Remarks
1			0-2 - TOPSOIL Roots, WET. DARK Brown.				1.6/1.6	
			2-2.5 Silt, Some Sand very stiff, non plastic					
5			Lt. brown, Dense, ~~DAMP~~ some Roots.				1.6/1.6	Sample Reading / background
			2.5 - ~~HS~~ 5.0, Silt, little Sand, DAMP, slightly plastic Stiff, Brn				1.6/1.6	
10							1.6/1.6	
			5-6.5 Silty Sand, Fine to med sand, non plastic silt, loose, DAMP. Lt. Brown				1.6/1.6	
15							1.9/1.9	
			6.5-7.5 - Silty Sand Fine to Med Sand Stiff, Brn, ~~MOIST~~ DAMP				1.6/1.6	
20			7.5-10 NO Recovery				1.6/1.6	
			10 - 12 weathered Siltstone little sand, mixed with silt cobble 2" diam Recovered, damp				2.2/2.2	
25								
			12-14 - Siltstone, damp slightly plastic, Stiff, Firm ~~ft~~					
30			14-15 Siltstone, damp sandy, slightly plastic Firm / Stiff, light brown				2.2/2.2	
			15-~~17~~ Siltstone, DAMP slightly Plastic, Med Stiff bedded w/ Stiff layers, med pebble gravel, Firm material bedded w/					
35								
40			17-19 SAA w/ more Firm					
			19-20 NO Recovery.					
			20-23 - Siltstone, sandy, wet slightly Plastic, med St. ft, Firm, some med pebble gravel.					
45			23-25 - No Recovery					

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GEOLOGIC BORING LOG

JOB NUMBER: 722450.30010 CLIENT: F.E. Warren AFB DATE: 4-27
BORING NUMBER: PCS4D BORING DIA.: 8.25 ELEVATION:
RIG TYPE: CONTRACTOR: Drilling Engineer DATUM: TOC
TEMPERATURE (°F): ~60° WEATHER: Cloudy GEOLOGIST: M. Sweeney, J. Bridgewater
DRLG MED: N/A
COMMENTS:

Depth (ft.)	Profile	USCS	Geologic Description	Split Spoon Interval	Laboratory Sample Identification	Sample Type	PID ppmv	Remarks
1			25-26 - Siltstone, some sand, firm, stiff, wet					
			26-27.5					
5			27-27.5 - Cobbly Gravel w/ course sand, wet, loose, non plastic					
			27.5-28.0					
			28-29 - med-coarse grain sand, wet, loose, non plastic, med brown					
10			29.0-29.5					
			29.5-32 - Sandy Gravel some silt, very coarse pebble gravel to cobble gravel bedded firm and loose wet, med brown					
15								
20			30-29.5-31.5 - S.A.A.					
			31.5-32.5 - silty Sandstone gray, sandwhich layered Fractures easily along layers. (br. Hz) DAMP.					photo taken
25								
			32.5-35 = S.A.A. hard but Brittle. DAMP. thinly layered Sandstone bedded w/ silt					
30			34.5					Stopped here 4-27
			35-36 - Sandstone, wet soft, firm, some silt. w/h,					Started here 4-28
35								
			36-36.5 Sandstone, stiff from Dense, wet	37			3.0/3.0	
			36.5-37 Sandstone some silt med, firm, wet					
40								
			37-37.5 - fine grain sandstone w/silt, firm, med stiff, wet					
			brown					
45								

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SS - Split Spoon Sample
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GEOLOGIC BORING LOG

JOB NUMBER: 722450.30010 CLIENT: F.E. Warren AFB DATE: 4-28-99
BORING NUMBER: PES 4D BORING DIA.: 8.25 OD 4.25 ID ELEVATION:
RIG TYPE: CONTRACTOR: Drilling Engineers DATUM:
TEMPERATURE (°F): 40 WEATHER: Foggy, windy GEOLOGIST:
DRLG MED: N/A
COMMENTS:

Depth (ft.)	Pro-file	USCS	Geologic Description	Split Spoon Interval	Laboratory Sample Identification	Sample Type	PID ppmv	Remarks
1			37.5-38.0 Fine to med grain Sandstone, med. ~~firm~~ stiff, firm, gray/brown, wet. non plastic					
5			38-39.5 - Fine grain Sandstone w/silt, firm, med stiff wet, brown	40			3.0/3.0	PID Sample/background
10			39.5-44.5- Fine grain Sandstone w/silt, firm, stiff ~~with~~ bedded with thin layers of very stiff and Dense Sandstone. wet.	42.5			3.0/3.0	
15			44.5-46.5. SAA	45			3.0/3.0	
20			46.5- Sandstone. 0.2' well cemented, very Dense 0.5' thick					
			47-49.5 no Recovery					
25								
30								
35								
40								
45								

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na - Not Analyzed
HS - Sample Headspace
SS - Split Spoon Sample
G - Grab Sample

Sheet 1 of 2

GEOLOGIC BORING LOG

JOB NUMBER:	722450.30010	CLIENT:	F.E. Warren AFB	DATE:	5/3/99
BORING NUMBER:	PES5D	BORING DIA.:	8.25 OD	ELEVATION:	
RIG TYPE:		CONTRACTOR:	Drilling Engineers	DATUM:	T.O.C
TEMPERATURE (°F):	50°	WEATHER:	50° windy	GEOLOGIST:	J. Bidgood
		DRLG MED:	N/A		

COMMENTS:

Depth (ft.)	Pro-file	USCS	Geologic Description	Split Spoon Interval	Laboratory Sample Identification	Sample Type	PID ppmv (Reading/Background)	Remarks
1			0-1 - Topsoil, pandy DARK Brown	0-4.5				
			1-1.5 - Sand, pebble cobbles,				1.6/1.3	
5			1.5-2.5 clay, stiff, Firm, plastic, moist.				1.9/1.6	
			2.5-4 silt, slightly plast stiff, Firm Damp					
10			4-4.5 NO Recovery				1.6/1.6	
			4.5-5.5 SANDSTONE, very weathered soft, mostly loose, nonplastic DAMP	4.5-9.5			2.1/1.3	
15								
			5.5-6 Claystone silty moist, med ~~Firm~~ stiff Firm,					
20								
			6-7.5 - claystone, moist Med brown, silty, Firm stiff, plastic					
25								
			7.5-8 Silt stone Firm Dry, sl. plastic					
30			8-9.5 - No Recovery,					
			9.5-10 - Fine Grain Sandstone, wet, silty, sl. clayey, med, stiff ~~no~~ mostly loose	9.5-14.5				
35								
			10-14.5 Silt stone, some sand Sam, clay sl. plastic Firm, stiff					
40			Layer of claystone at 12.5 ~~12~~ ~0.1' thick, moist					
			14.5-~~19.5~~ 15.5 Siltstone, some fine grain SAND, little clay, plastic, wet, stiff, Firm.	14.5-19.5				
45			15.5-19.5 No Recovery					

NOTES:

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TOC - Top of Casing

na - Not Analyzed
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G - Grab Sample

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Sheet 2 of 2

GEOLOGIC BORING LOG

JOB NUMBER:	722450.30010	CLIENT:	F.E. Warren AFB	DATE:	5-3-99
BORING NUMBER:	PES SD	BORING DIA.:	8.25" OD, 4.25 ID	ELEVATION:	
RIG TYPE:		CONTRACTOR:	Drilling Engineers	DATUM:	T.O.C
TEMPERATURE (°F):	50°	WEATHER:	Windy, cloudy	GEOLOGIST:	J. Bidgood
		DRLG MED:	N/A		
COMMENTS:					

Depth (ft.)	Pro-file	USCS	Geologic Description	Split Spoon Interval	Laboratory Sample Identification	Sample Type	PID ppmv	Remarks
1			19.5-24.5 Fine Grain Sandstone, some silt, little clay, plastic, med brown wet, Firm, stiff.	19.5-24.5				
5								Stoped Here on 5-3
			19.5-21.5 SAA.	24.5-29.5				
			21.5-24.5 - Sandstone, ~~Fine~~ Med to coarse grain, ~~&~~ Firm, stiff, wet, med brown, silty sl. plastic					
10								
			29.5-30.5 - SAA	29.5-34.5				
15			30.5-34.5 - ~~SAA~~ Fine Grain sandstone, some silt, slightly plastic, med brown, wet Firm, stiff.					
20			34.5-49.5 - Fine grain sandstone some silt, sl. plastic, med brown, wet, Firm stiff.					screened 34.5-39.5
25								
30								
35								
40								
45								

NOTES:

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BGS - Below Ground Surface
TOC - Top of Casing

na - Not Analyzed
HS - Sample Headspace
SS - Split Spoon Sample
G - Grab Sample

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GEOLOGIC BORING LOG

JOB NUMBER: 722450.30010
BORING NUMBER: BES65
RIG TYPE: SME 75
TEMPERATURE (°F): 45°F
COMMENTS:

CLIENT: F.E. Warren AFB
BORING DIA.: 8.25 OD 4.25 ID
CONTRACTOR: Drilling Dynamics
WEATHER: 45° clear, breezy
DRLG MED: N/A

DATE: 4-27-99
ELEVATION:
DATUM: TOC
GEOLOGIST: M. Reimer (J. Bidgood)

readings follow stab

Depth (ft.)	Pro-file	USCS	Geologic Description	Split Spoon Interval	Laboratory Sample Identification	Sample Type	PID ppmv	Remarks
1			0-1 - Top soil, wet, brown roots					
			1-2 - clay, silty, med brown moist, cobble 3" diam				0.3	
5							0.3	
			2-4.5 - silt, clayey, grey, damp, non plastic med stiff				0.3	
10								
			4.5-5 - SAA				0.3	
			5-6 (Silt) Very Sandy lt brown stiff, non plastic moist Damp.				0.5	
15	Sandy Silt						0.3	
			6-7' (Silt) clayey (lt brown) Damp, med stiff, film				0.0	
20	Clayey Silt		7-7.5 Silt, clayey, stiff brown, Damp, film				0.3	
			7.5-9.5 no Recovery				0.5	
25			9.5-14.5 silt, some sand trace clay				0.8	
			9.5-10.5 silt, some sand trace clay (lt brown) Moist slightly Plastic, Stiff				2.2/2.1	Reading/Background
30	Sand Silt		10.5-14.5 Silt, some sand trace clay, (lt brown) Damp, slightly plastic, stiff				2.2/2.1	" / "
35			14.5-16 Silt some sand trace clay, stiff, film moist, light brown slightly plastic					
40			16-18 - silt some sand, trace clay, stiff film Damp slightly plastic light brown					
45								

NOTES:
PID - Photoionization Detector
ppmv - Parts per Million, Volume per Volume
BGS - Below Ground Surface
TOC - Top of Casing
na - Not Analyzed
HS - Sample Headspace
SS - Split Spoon Sample
G - Grab Sample

GEOLOGIC BORING LOG

JOB NUMBER:	722450.30010	CLIENT:	F.E. Warren AFB	DATE:	4-27-97
BORING NUMBER:	PES 65	BORING DIA.:	8.25	ELEVATION:	
RIG TYPE:	SME 75	CONTRACTOR:	Drilling Engineering	DATUM:	TOC
TEMPERATURE (°F):	58	WEATHER:	Clear breezy	GEOLOGIST:	M. Reimann (J. Bidgoo)
		DRLG MED:	N/A		
COMMENTS:					

Depth (ft.)	Pro-file	USCS	Geologic Description	Split Spoon Interval	Laboratory Sample Identification	Sample Type	PID ppmv	Remarks
1			18 - 18.5 ~~Silt, Some Sand~~ trace clay, very ~~firm~~ stiff firm, Damp.					
5			18.5-19.5 - Silt, Some sand trace clay med stiff, firm Damp. lt. brown					
10			19.5-21 - fine sand, some silt moist, slightly plastic soft, firm, lt brown		Silty Sand			
15			21.-23.5 - fine sand, some silt Damp, Slighty Plastic Stiff, firm					
			23.5-24.5 Silt, Some fine sand, medium stiff, firm Dry.		Sandy Silt			
20			24.5-27 Very weathered sandstone, mixed w/silt (erosional zone), pieces of sand-stone are pebbly gravel size slightly plastic Damp.		~25' weathered			
25			27.5-28.5 - sand stone some silt, friable stiff, firm, lt. brown/gray DRY.					
30			28.5-29.5, Silty Claystone occassional 1/2" thick layers Sandstone very stiff, firm Damp., Lt. brown		Siltstone/Claystone			
35			29.5-32 - thinly layered Alternating silt stone Sandstone very firm, stiff. Damp.					
40								
45								

NOTES:

PID - Photoionization Detector
ppmv - Parts per Million, Volume per Volume
BGS - Below Ground Surface
TOC - Top of Casing

na - Not Analyzed
HS - Sample Headspace
SS - Split Spoon Sample
G - Grab Sample

GEOLOGIC BORING LOG

JOB NUMBER:	722450.30010	CLIENT:	F.E. Warren AFB	DATE:	4-26-99
BORING NUMBER:	PES 6D	BORING DIA.:	8.25 OD @ 4.25 ID	ELEVATION:	
RIG TYPE:	CME 75	CONTRACTOR:	Drilling Engineers	DATUM:	T.O.C.
TEMPERATURE (°F):	50°	WEATHER:	partly cloudy wind NW 5-15 mph	GEOLOGIST:	M. Zeiman
		DRLG MED:	N/A		

COMMENTS:

PID Background reading 1.7 ppm

PID Reading w/ scale

Depth (ft.)	Pro-file	USCS	Geologic Description	Split Spoon Interval	Laboratory Sample Identification	Sample Type	PID ppmv	Remarks
1			0-1' Top soil, silty, some sand and gravel, roots/grass, wet					
			1-4.0' - silt, slightly stiff, some light grayish brown, Dry				1.9	
4.5	cobbles silt							
5			4'-4.5 silt, light gray, soft loose, Dry, no odor/stain				2.4	
			4.5-5 SAA, cobble 1" Diam					
			5-5.5 silt, med brownish brown, med. plastic, damp, some fine sand				2.4	
10	Sandy silt		5.5-6 silt, very sandy, light gray, somewhat cemented, very stiff				1.9	
	clayey silt							
			9.5-14.5 silt w/ fine sand, med med gray brown, slightly plastic soft, Damp, no clay no odor/stain				2.2	
15	Sandy silt						2.2	
			~~14.5-19.5 SAA~~					
			14.5-18' silt, slightly sandy med. plast, sl. stiff, light brown no odor/stain				2.2	
20							2.2	17.5 = 1.9 ppm
			18-19.5 silt, very sandy med pl. sl. stiff., sl. loose, DAMP, light brown				~~1.7~~	20' = 1.7 ppm
	Silty sand						2.2	
25			19.5-~~24.5~~-23.5- SAA				2.2	
			~~23.5-24.5 silt, banded w/ brown silt gray, Dry~~				1.9	
			<3.5-24.5 silt, Dry, loose, brittle w/ med. brown bands,					
30			~~28.0~~ 26.0'				1.9	Water @ 30'
	~25-28 Weathered		24.5 ~~29.5~~ - ~~Sandy~~ silt, v. sandy very moist, light brown occasional cobbles 1-2.5" diam				2.4	
35			~~28.29.5~~ - 26.5 - 28.5 weathered sandstone ? fine grain, sl silty med cemented weathered	28' Siltstone			2.4	
			28.5-29.5, siltstone, clayey, light brown, soft, sl. plastic, Damp				3.4	
40			29.5-31' sandstone, silty, brittle med. cemented, light gray,	Sandstone			3.4	
			31-32' sandstone, v silty, layered brittle, gray/light brown, DRY				2.2	
			32-32.5, ~~siltstone~~ claystone, silty, brittle, v. stiff, light brown, DRY				3.4	
45							2.4	

NOTES:

PID - Photoionization Detector
ppmv - Parts per Million, Volume per Volume
BGS - Below Ground Surface
TOC - Top of Casing

na - Not Analyzed
HS - Sample Headspace
SS - Split Spoon Sample
G - Grab Sample

PARSONS ENGINEERING SCIENCE, INC.

S:\ES\REMED\BIOPLUME\FEWARREN\WORKPLAN\TABLES\WP-Tabels.xls/BRNGLOG

GEOLOGIC BORING LOG

JOB NUMBER:	722450.30010	CLIENT:	F.E. Warren AFB	DATE:	4-26-99
BORING NUMBER:	PES 6D	BORING DIA.:	3.25 OD 4.25 ED	ELEVATION:	
RIG TYPE:		CONTRACTOR:	Drilling Engineer	DATUM:	
TEMPERATURE (°F):		WEATHER:		GEOLOGIST:	M. Reiman
		DRLG MED:	N/A		

COMMENTS: Auger Removed and grouted on 4-27

Depth (ft.)	Pro-file	USCS	Geologic Description	Split Spoon Interval	Laboratory Sample Identification	Sample Type	PID ppmv	Remarks
1			32.5 - 33.5, Sand Stone, silty layered, grey/light brown, platey brittly, Dry					
5			29.5 - 34.5 - siltstone, Damp, ~~light~~ brown, stiff, med brown bands					
10			34.5 - ~~37.5~~ - 37.5 silty clay stone light brown, slightly plastic, ~~Damp~~ wet					
			36.5 - 38, clay, silty, brown wet, very plastic					Photos 3, & 4
15			38 - 39.5 silty Sandstone brown					
			~~39.5 - 44.5 - silty Silt, very sandy (fine sand) somewhat plastic, light brown wet, somewhat consolidated brittle~~					Photos 5 and 6
20			39.5 - 44.5 = fine Sand, silty, brown, somewhat consolidated, somewhat plastic wet.					
25								
30								
35								
40								
45								

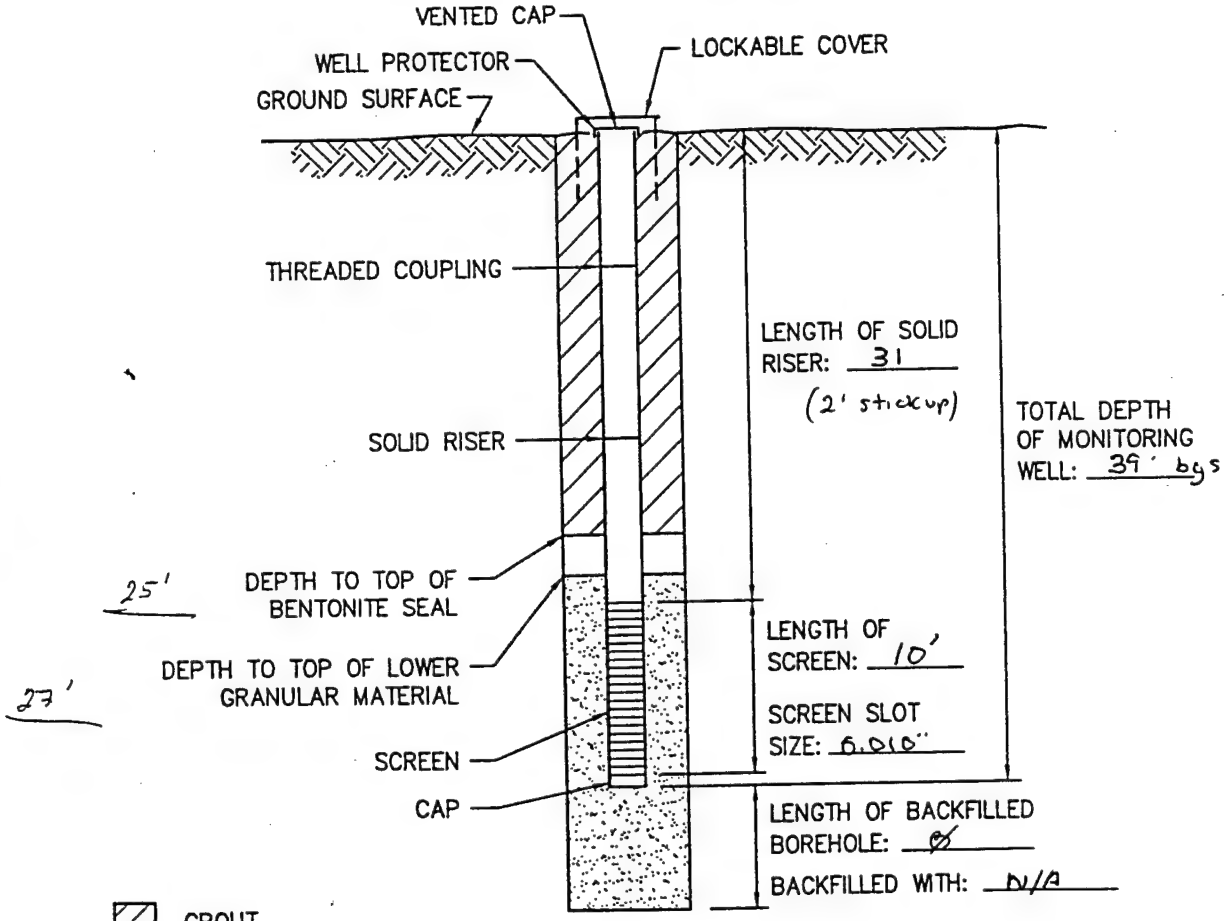
NOTES:

PID - Photoionization Detector
ppmv - Parts per Million, Volume per Volume
BGS - Below Ground Surface
TOC - Top of Casing

na - Not Analyzed
HS - Sample Headspace
SS - Split Spoon Sample
G - Grab Sample

SINGLE-CASED MONITORING WELL INSTALLATION RECORD

JOB NAME F.E. WARREN AFB LF-03 WELL NUMBER PES 15
JOB NUMBER 722450 INSTALLATION DATE 4-30-99 LOCATION LF-03
DATUM ELEVATION _____ GROUND SURFACE ELEVATION _____
DATUM FOR WATER LEVEL MEASUREMENT T.O.C (PVC)
SCREEN DIAMETER & MATERIAL 2" PVC SLOT SIZE 0.010"
RISER DIAMETER & MATERIAL 2" PVC BOREHOLE DIAMETER 8.25" OD
GRANULAR BACKFILL MATERIAL 20-40 Sand ES REPRESENTATIVE J. BIDGOOD
DRILLING METHOD HOLLOW STEM AUGER DRILLING CONTRACTOR Drilling Engineers



(NOT TO SCALE)

STABILIZED WATER LEVEL _____ FEET BELOW DATUM.
MEASURED ON _____

FIGURE 3.3

SINGLE-CASED MONITORING WELL INSTALLATION RECORD

Site LF-03 RNA TS
F.E. Warren AFB, Wyoming

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

SINGLE-CASED MONITORING WELL INSTALLATION RECORD

JOB NAME F.E. WARREN AFB LF-03 WELL NUMBER PES 2D

JOB NUMBER 722450 INSTALLATION DATE 4-29-99 LOCATION LF03

DATUM ELEVATION _____ GROUND SURFACE ELEVATION _____

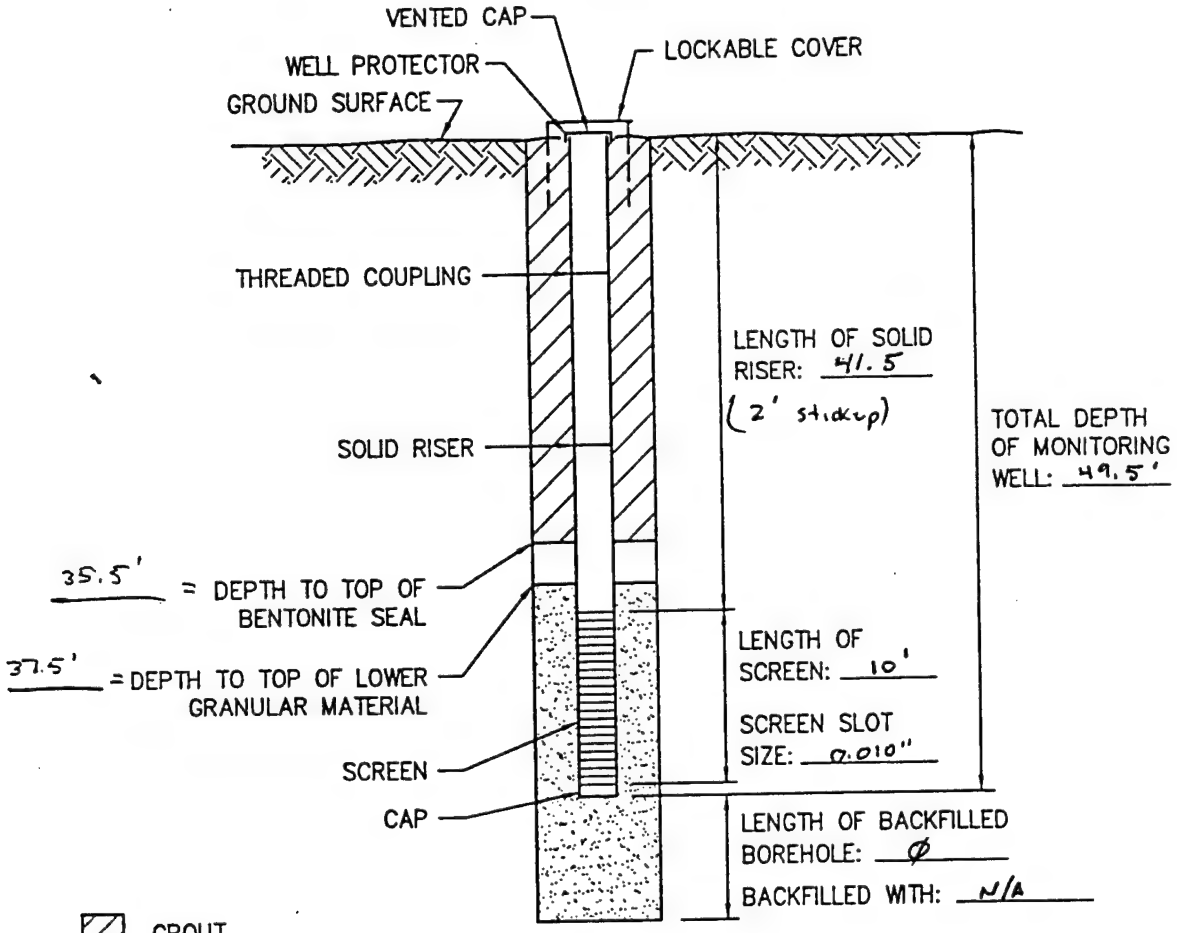
DATUM FOR WATER LEVEL MEASUREMENT T.O.C.

SCREEN DIAMETER & MATERIAL 2" PVC SLOT SIZE 0.010"

RISER DIAMETER & MATERIAL 2" PVC BOREHOLE DIAMETER 8.25"

GRANULAR BACKFILL MATERIAL 20-40 sand ES REPRESENTATIVE M. Reimann, J. Bidgood

DRILLING METHOD HOLLOW STEM AUGER DRILLING CONTRACTOR Drilling Engineers



(NOT TO SCALE)

STABILIZED WATER LEVEL _____ FEET BELOW DATUM.
MEASURED ON _____

FIGURE 3.3

SINGLE-CASED MONITORING WELL INSTALLATION RECORD

Site LF-03 RNA TS
F.E. Warren AFB, Wyoming

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

SINGLE-CASED MONITORING WELL INSTALLATION RECORD

JOB NAME F.E. WARREN AFB LF-03 WELL NUMBER PES 3D

JOB NUMBER 722450 INSTALLATION DATE 5-4-99 LOCATION LF-03

DATUM ELEVATION _____ GROUND SURFACE ELEVATION _____

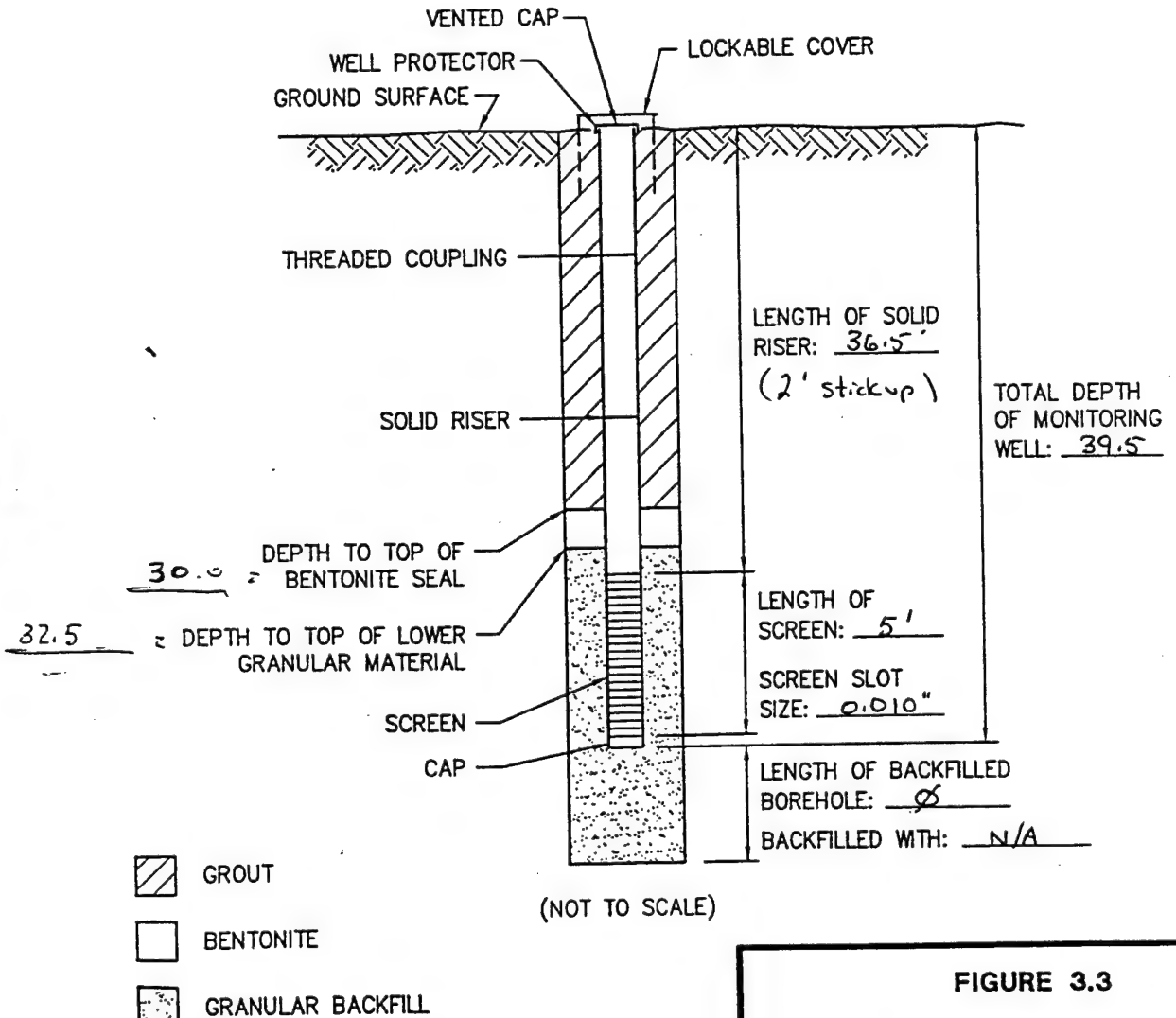
DATUM FOR WATER LEVEL MEASUREMENT T.O.C

SCREEN DIAMETER & MATERIAL 2" PVC SLOT SIZE 0.010"

RISER DIAMETER & MATERIAL 2" PVC BOREHOLE DIAMETER 8.25" O.D.

GRANULAR BACKFILL MATERIAL 20-40 Sand ES REPRESENTATIVE J. Biddoop

DRILLING METHOD HOLLOW STEM AUGER DRILLING CONTRACTOR Drilling Engineers



STABILIZED WATER LEVEL 8.22 FEET BELOW DATUM.
MEASURED ON 5/4/99 , 15:52

FIGURE 3.3

SINGLE-CASED MONITORING WELL INSTALLATION RECORD

Site LF-03 RNA TS
F.E. Warren AFB, Wyoming

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

SINGLE-CASED MONITORING WELL INSTALLATION RECORD

JOB NAME F.E. WARREN AFB LF-03 WELL NUMBER PES 4D

JOB NUMBER 722450 INSTALLATION DATE 4-28-99 LOCATION LF03

DATUM ELEVATION _____ GROUND SURFACE ELEVATION _____

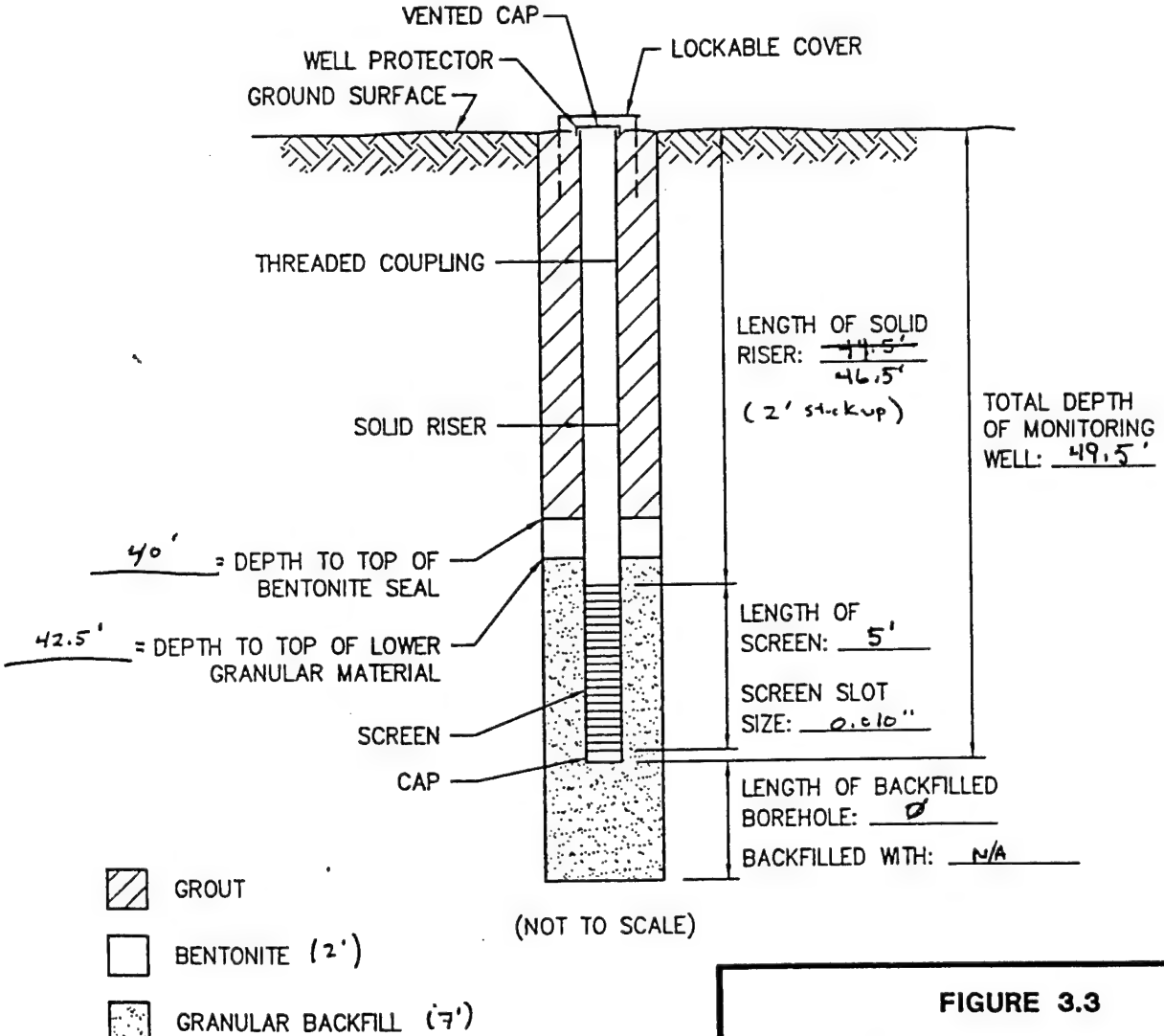
DATUM FOR WATER LEVEL MEASUREMENT TOC

SCREEN DIAMETER & MATERIAL 2" PVC SLOT SIZE 0.010"

RISER DIAMETER & MATERIAL 2" PVC BOREHOLE DIAMETER 8.25"

GRANULAR BACKFILL MATERIAL 20-40 sand ES REPRESENTATIVE M. Beimann, J. Bidgood

DRILLING METHOD HOLLOW STEM AUGER DRILLING CONTRACTOR Drilling Engineers



(NOT TO SCALE)

STABILIZED WATER LEVEL _____ FEET BELOW DATUM.
MEASURED ON _____

FIGURE 3.3

SINGLE-CASED MONITORING WELL INSTALLATION RECORD

Site LF-03 RNA TS
F.E. Warren AFB, Wyoming

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

SINGLE-CASED MONITORING WELL INSTALLATION RECORD

JOB NAME F.E. WARREN AFB LF-03 WELL NUMBER PES 5D

JOB NUMBER 722450 INSTALLATION DATE 5-4-99 LOCATION LF-03

DATUM ELEVATION ~~TOC~~ GROUND SURFACE ELEVATION _____

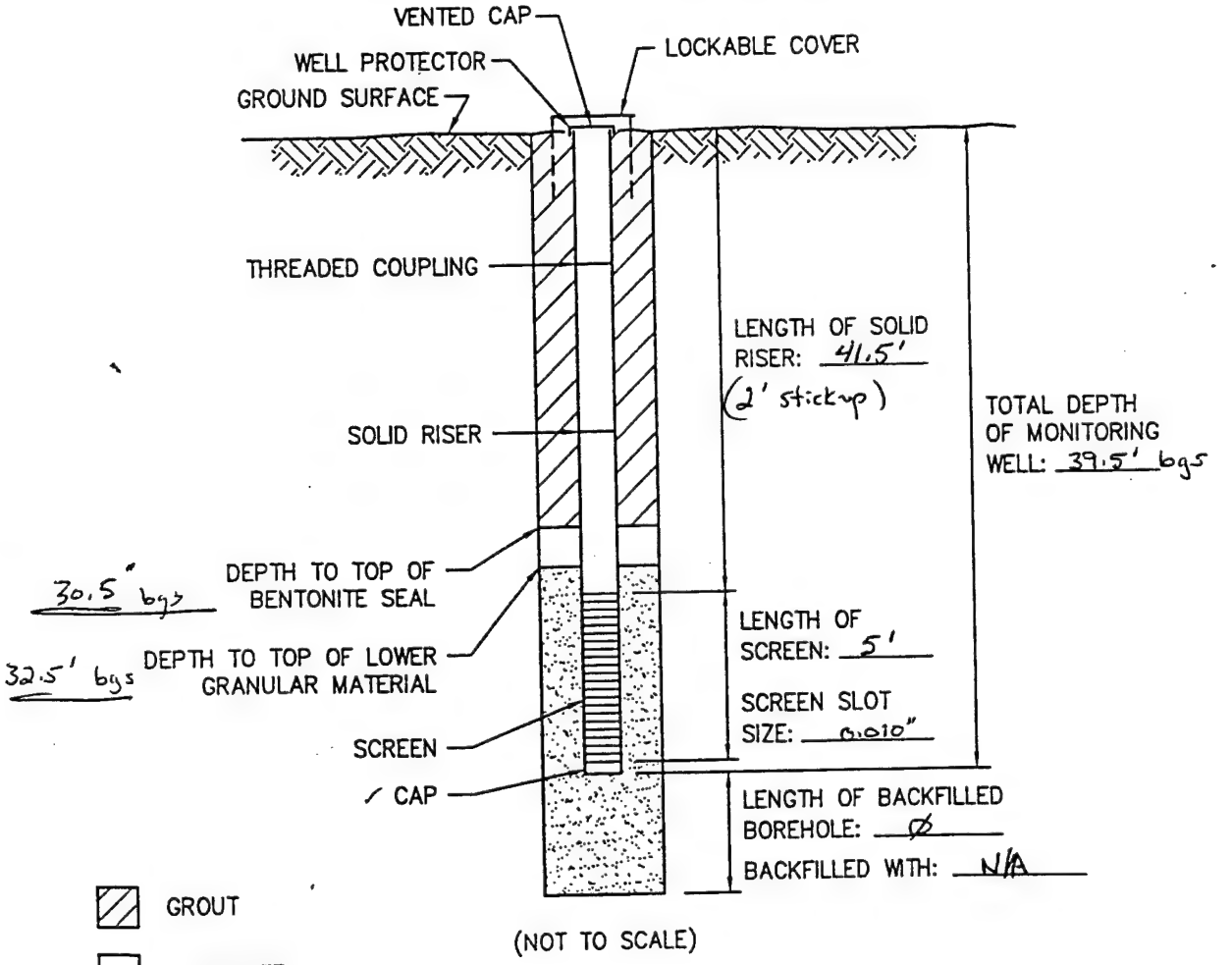
DATUM FOR WATER LEVEL MEASUREMENT T.O.C

SCREEN DIAMETER & MATERIAL 2" PVC SLOT SIZE 0.010"

RISER DIAMETER & MATERIAL 2" PVC BOREHOLE DIAMETER 8.25"

GRANULAR BACKFILL MATERIAL 20-40 Sand ES REPRESENTATIVE J. Bidgood

DRILLING METHOD HOLLOW STEM AUGER DRILLING CONTRACTOR Drilling Engineers



STABILIZED WATER LEVEL _____ FEET BELOW DATUM.
MEASURED ON _____

FIGURE 3.3

SINGLE-CASED MONITORING WELL INSTALLATION RECORD

Site LF-03 RNA TS
F.E. Warren AFB, Wyoming

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

SINGLE-CASED MONITORING WELL INSTALLATION RECORD

JOB NAME F.E. WARREN AFB LF-03 WELL NUMBER PES 65

JOB NUMBER 722450 INSTALLATION DATE 4-27-97 LOCATION LF03

DATUM ELEVATION _____ GROUND SURFACE ELEVATION _____

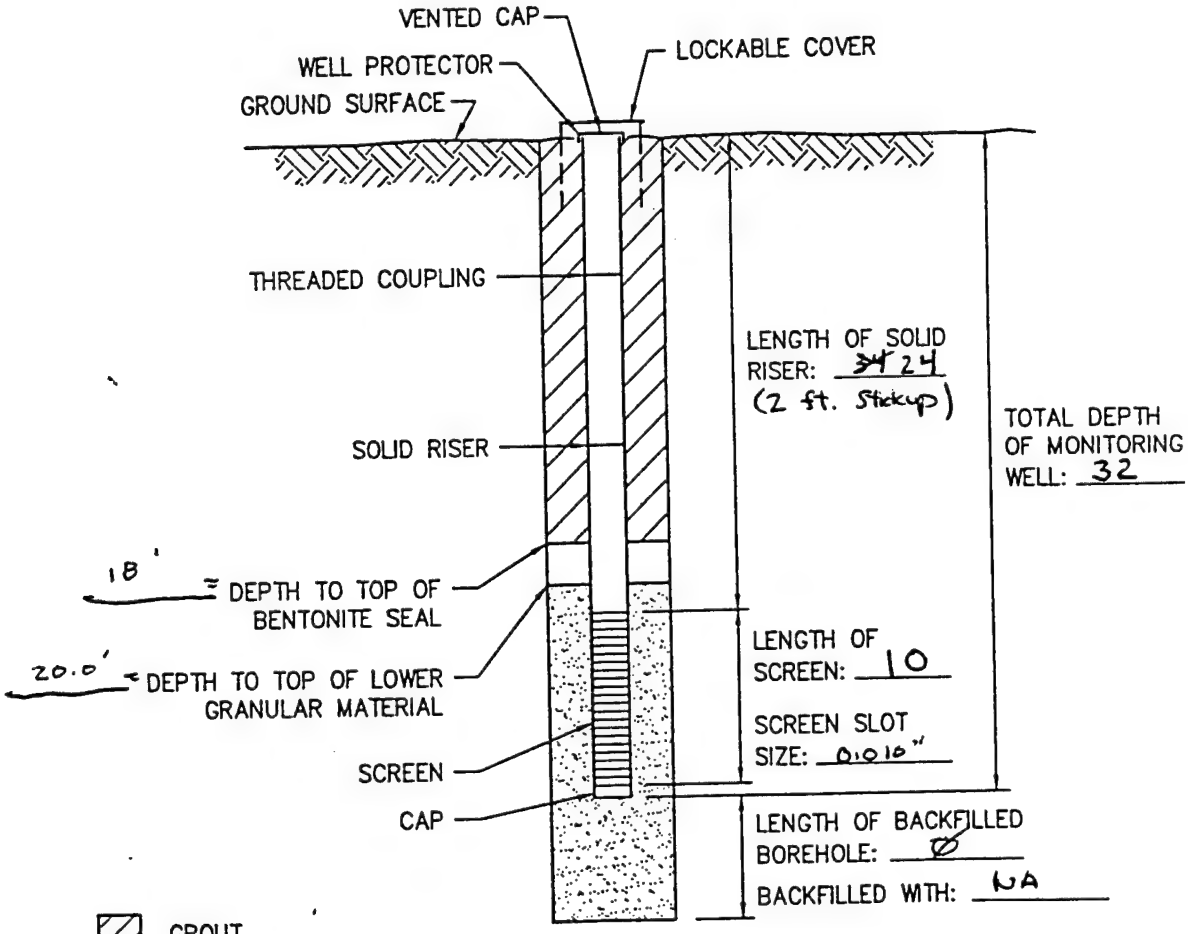
DATUM FOR WATER LEVEL MEASUREMENT TOC

SCREEN DIAMETER & MATERIAL 2" PVC SLOT SIZE 0.010"

RISER DIAMETER & MATERIAL 2" PVC BOREHOLE DIAMETER 8.25"

GRANULAR BACKFILL MATERIAL 20-40 SAND ES REPRESENTATIVE J. Bidgood, N. Reimann

DRILLING METHOD HOLLOW STEM AUGER DRILLING CONTRACTOR Drilling Engineers



STABILIZED WATER LEVEL 14.32 FEET (14:00) BELOW DATUM. MEASURED ON 4-27-99

FIGURE 3.3

SINGLE-CASED MONITORING WELL INSTALLATION RECORD

Site LF-03 RNA TS
F.E. Warren AFB, Wyoming

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

SINGLE-CASED MONITORING WELL INSTALLATION RECORD

JOB NAME F.E. WARREN AFB LF-03 WELL NUMBER PES 6D

JOB NUMBER 722450 INSTALLATION DATE 4-26-99 LOCATION LF03

DATUM ELEVATION _____ GROUND SURFACE ELEVATION _____

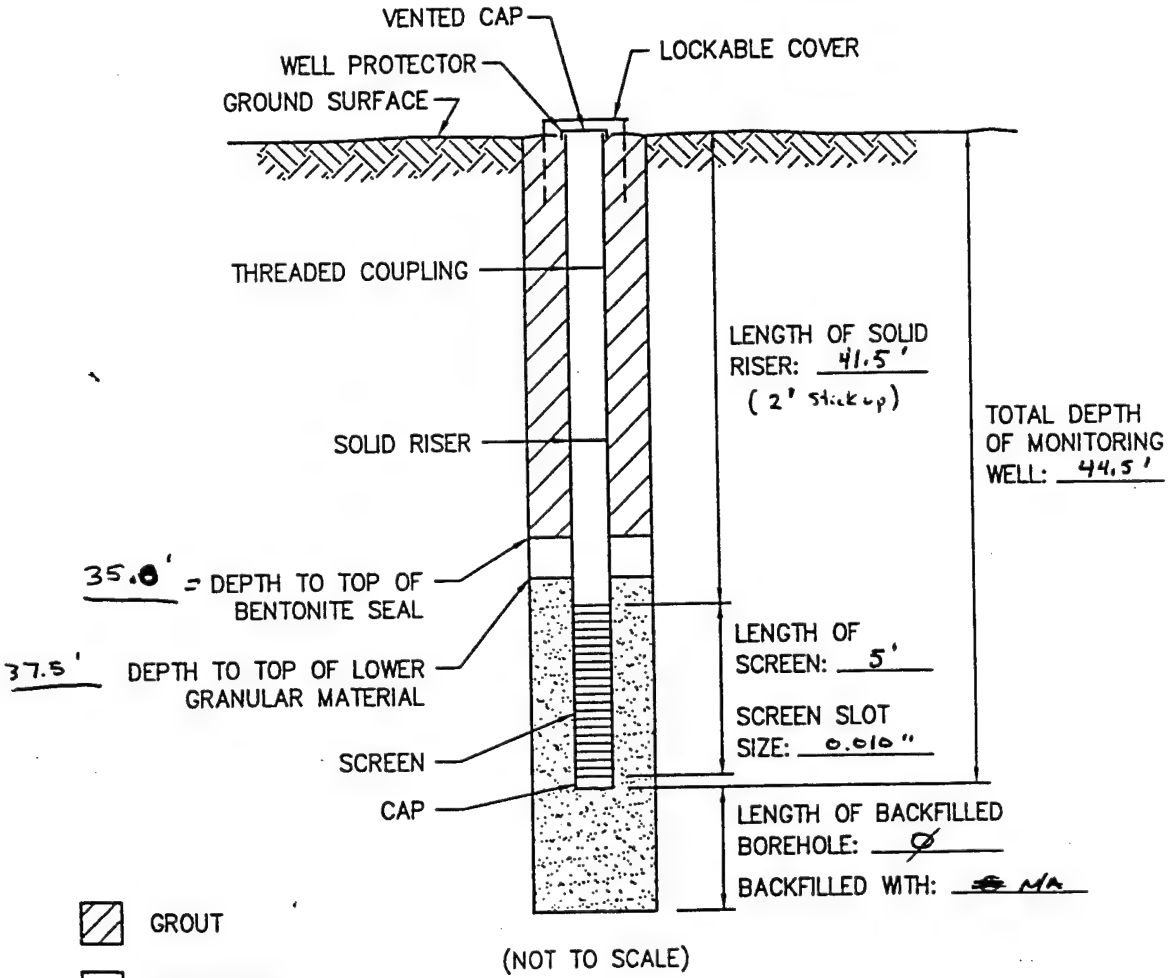
DATUM FOR WATER LEVEL MEASUREMENT TOC

SCREEN DIAMETER & MATERIAL 2" PVC SLOT SIZE 0.010 in

RISER DIAMETER & MATERIAL 2" PVC BOREHOLE DIAMETER 8.25"

GRANULAR BACKFILL MATERIAL Sand 20-40 ES REPRESENTATIVE J. Bidgood, M. Brennan

DRILLING METHOD HOLLOW STEM AUGER DRILLING CONTRACTOR Drilling Engineers



(NOT TO SCALE)

STABILIZED WATER LEVEL 25.69 FEET BELOW DATUM.
MEASURED ON 4-27-99

FIGURE 3.3

SINGLE-CASED MONITORING WELL INSTALLATION RECORD

Site LF-03 RNA TS
F.E. Warren AFB, Wyoming

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

MONITORING WELL DEVELOPMENT RECORD

Well Identification ~~PES 4D~~ PES 15
Job Number: 722450 Job Name: AFCEE-RNA
Location F.E. Warren AFB - LF-03 by JBB Date: 5-3-99

Measurement Datum TOC

Pre-Development Information Time (Start): 1050

Water Level: _____ Total Depth of Well: _____

Water Characteristics

Color _____ Clear (Cloudy)
Odor: None Weak Moderate Strong
Any Films or Immiscible Material _____
pH _____ Temperature (°C) _____
Specific Conductance (µS/cm) _____
Dissolved Oxygen (mg/L) _____
Redox (mV) _____

Interim Water Characteristics

Gallons Removed 12

pH 8.00

Temperature (°C) 10.7

Specific Conductance(µS/cm) 1141 µS

Dissolved Oxygen (mg/L) 2.39

Redox (mV) 108.5 mV

Post-Development Information Time (Finish): 5/6/99 - 10:10

Water Level: 28.88 ft below TOC Total Depth of Well: _____

Approximate Volume Removed: _____

Water Characteristics

Color _____ Clear Cloudy
Odor: (None) Weak Moderate Strong
Any Films or Immiscible Material none
pH 7.09 Temperature (°C) 10.3
Specific Conductance (µS/cm) 1182
Dissolved Oxygen (mg/L) 1.17
Redox (mV) + 103

Comments:

MONITORING WELL DEVELOPMENT RECORD

Well Identification PES-2D
Job Number: 722450 Job Name: AFCEE-RNA
Location F.E. Warren AFB - LF-03 by _____ Date: 5-3-99

Measurement Datum T.O.C

Pre-Development Information Time (Start): 1144

Water Level: 20.78 below TOC Total Depth of Well: 49.96' From TOC.

Water Characteristics

Color White/Gray Clear Cloudy
Odor: (None) Weak Moderate Strong
Any Films or Immiscible Material _____
pH 8.22 Temperature (°C) 12.4
Specific Conductance (µS/cm) 610
Dissolved Oxygen (mg/L) 3.63
Redox (mV) ~~120~~ 122.5

Interim Water Characteristics

Gallons Removed ~~[illegible]~~

pH _____

Temperature (°C) ~~12.4~~

Specific Conductance(µS/cm) _____

Dissolved Oxygen (mg/L) ~~3.63~~

Redox (mV) _____

Post-Development Information Time (Finish): 0915 on 5-6-99

Water Level: 20.75' b. T.O.C Total Depth of Well: _____

Approximate Volume Removed: _____

Water Characteristics

Color _____ Clear Cloudy
Odor: (None) Weak Moderate Strong
Any Films or Immiscible Material _____
pH 6.92 Temperature (°C) 9.5
Specific Conductance (µS/cm) 826
Dissolved Oxygen (mg/L) 1.79
Redox (mV) +184.6

Comments:

$V = 4.7$ $10 \times V = 47$ gal.

MONITORING WELL DEVELOPMENT RECORD

Well Identification PES-3D
Job Number: 722450
Location F.E. Warren AFB - LF-03

Job Name: AFCEE-RNA
by J. Bidgood, AIR, Date: 5-5-99

Measurement Datum T.O.C.

Pre-Development Information

Time (Start): 11:30

Water Level: _____ Total Depth of Well: _____

Water Characteristics

Color light brown Clear (Cloudy)
Odor: None Weak Moderate Strong
Any Films or Immiscible Material _____
pH _____ Temperature (°C) 10.1
Specific Conductance (µS/cm) _____
Dissolved Oxygen (mg/L) +
Redox (mV) _____

Interim Water Characteristics

Gallons Removed 5

pH _____

Temperature (°C) 10.0

Specific Conductance(µS/cm) 681

Dissolved Oxygen (mg/L) 1.47

Redox (mV) 91.0

Post-Development Information

Time (Finish): 5/6/99 10:20

Water Level: 17.5 below T.O.C. Total Depth of Well: _____

Approximate Volume Removed: _____

Water Characteristics

Color _____ Clear Cloudy
Odor: (None) Weak Moderate Strong
Any Films or Immiscible Material none
pH NA Temperature (°C) 10.0
Specific Conductance (µS/cm) 407
Dissolved Oxygen (mg/L) 5.16
Redox (mV) 149.6

Comments:

MONITORING WELL DEVELOPMENT RECORD

Well Identification PES-4D
Job Number: 722450
Location F.E. Warren AFB - LF-03

Job Name: AFCEE-RNA
by ARC Date: 5/2/99

Measurement Datum TOP OF PVC PIPE

Pre-Development Information Time (Start): 9:30 AM

Water Level: 16.76' Total Depth of Well: 52.3'

Water Characteristics

Color _____ Clear ~~Cloudy~~
Odor: None Weak Moderate Strong
Any Films or Immiscible Material _____
pH _____ Temperature (°C) _____
Specific Conductance (µS/cm) _____
Dissolved Oxygen (mg/L) _____
Redox (mV) _____

Interim Water Characteristics

Gallons Removed 7

pH 8.44

Temperature (°C) 10.6

Specific Conductance(µS/cm) 233

Dissolved Oxygen (mg/L) 1.67

Redox (mV) 85.2

Post-Development Information Time (Finish): 5/5/99

Water Level: 18.58' below T.O.C. Total Depth of Well: _____

Approximate Volume Removed: _____

Water Characteristics

Color _____ Clear Cloudy
Odor: ~~None~~ Weak Moderate Strong
Any Films or Immiscible Material None
pH 7.81 Temperature (°C) 11.4
Specific Conductance (µS/cm) 406
Dissolved Oxygen (mg/L) 2.07
Redox (mV) + 171.0

Comments:

MONITORING WELL DEVELOPMENT RECORD

Well Identification PES-5D
Job Number: 722450
Location F.E. Warren AFB - LF-03

Job Name: AFCEE-RNA
by J. Blood, A Tubbs Date: 5-5-99

Measurement Datum T.O.C

Pre-Development Information

Time (Start):

Water Level:

Total Depth of Well: 3 42' From T.O.C

Water Characteristics

Color Turbid - light brown Clear ~~Cloudy~~
Odor: ~~None~~ Weak Moderate Strong
Any Films or Immiscible Material None
pH Temperature (°C)
Specific Conductance (µS/cm)
Dissolved Oxygen (mg/L)
Redox (mV)

Interim Water Characteristics

Gallons Removed 4

pH

Temperature (°C) 14.4

Specific Conductance(µS/cm) 1788 µS

Dissolved Oxygen (mg/L) 4.51 mg/L

Redox (mV) 114.3 mV

Post-Development Information

Time (Finish): 5/6/99

Water Level: 7.3' below TOC

Total Depth of Well:

Approximate Volume Removed:

Water Characteristics

Color Clear Cloudy
Odor: (None) Weak Moderate Strong
Any Films or Immiscible Material None
pH N/A Temperature (°C) 13.1
Specific Conductance (µS/cm) 1149
Dissolved Oxygen (mg/L) 4.03
Redox (mV) 130.5

Comments:

MONITORING WELL DEVELOPMENT RECORD

Well Identification PES 6S
Job Number: 722450
Location F.E. Warren AFB - LF-03

Job Name: AFCEE-RNA
by JBB Date: 5-3-99

Measurement Datum T.O.C.

Pre-Development Information

Time (Start): 0930

Water Level: 14.32 measured 4/27/99

Total Depth of Well: 32

Water Characteristics

Color _____ Clear Cloudy
Odor: None Weak Moderate Strong
Any Films or Immiscible Material _____
pH _____ Temperature (°C) _____
Specific Conductance (µS/cm) _____
Dissolved Oxygen (mg/L) _____
Redox (mV) _____

Interim Water Characteristics

Gallons Removed 10 gal.

pH 8.44

Temperature (°C) 10.2

Specific Conductance(µS/cm) 509

Dissolved Oxygen (mg/L) 5.61

Redox (mV) 127.4

Post-Development Information

Time (Finish): 09:15, 5/3/99

Water Level: 12.90 Ft. b. TOC.

Total Depth of Well: _____

Approximate Volume Removed: _____

Water Characteristics

Color _____ Clear Cloudy
Odor: None Weak Moderate Strong
Any Films or Immiscible Material none
pH 7.38 Temperature (°C) 9.1
Specific Conductance (µS/cm) 851
Dissolved Oxygen (mg/L) 2.76
Redox (mV) 141.8

Comments:

I:\forms\develop.doc

casing vol = 2.9 gal 10 v = 29 gal

MONITORING WELL DEVELOPMENT RECORD

Well Identification PES-6D
Job Number: 722450 Job Name: AFCEE-RNA
Location F.E. Warren AFB - LF-03 by MLP Date: 5/2/99

Measurement Datum Top of PVC Casing

Pre-Development Information Time (Start):

Water Level: 25.69 below TOC Total Depth of Well: 44.5

Water Characteristics

Color Clear Cloudy
Odor: None Weak Moderate Strong
Any Films or Immiscible Material
pH Temperature (°C)
Specific Conductance (µS/cm)
Dissolved Oxygen (mg/L)
Redox (mV)

Interim Water Characteristics

Gallons Removed 8 gallons
pH 9.8
Temperature (°C) 11.3 °C
Specific Conductance(µS/cm) 364.4 µS/cm
Dissolved Oxygen (mg/L) 6.51 mg/L Turbidity > 1000 NTU
Redox (mV) 118.7 mV

Post-Development Information Time (Finish):

Water Level: Total Depth of Well:

Approximate Volume Removed:

Water Characteristics

Color Clear Cloudy
Odor: ~~None~~ Weak Moderate Strong
Any Films or Immiscible Material none
pH 8.14 Temperature (°C) 10.6
Specific Conductance (µS/cm) 317
Dissolved Oxygen (mg/L) 3.48
Redox (mV) 137.1

Comments:

Casing Vol = 3.1 gal 10 x V = 31 gal

Groundwater Sampling Record Warren AFB.
Monitoring Well No. MW-62 5-5-99

[ ] SAMPLE EXTRACTION METHOD:

[ ] Bailer made of: _____
[x] Pump. type: Bennett
[ ] Other, describe: _____

Sample obtained is [X] GRAB; [ ] COMPOSITE SAMPLE

6 [ ] ON-SITE MEASUREMENTS:

Time	821	825	829			Measured with
Temp (°C)	9.2	9.1	9.1			
pH	7.18	7.39	7.45			
Cond (µS/cm)	572	563	556			
DO (mg/L)	2.72	2.73	2.65			
Redox (mV)	+158	+171	+177			
Salinity	—	—	—			

7 [ ] SAMPLE CONTAINERS (material, number, size): _____

Check-off

1 [ ] EQUIPMENT CLEANED BEFORE USE WITH: _____
Items Cleaned (List): _____

2 [ ] PRODUCT DEPTH: _____ FT. BELOW DATUM
Measured with: _____

WATER DEPTH: 19.32 Ft FT. BELOW DATUM
Measured with: Solinst

3 [ ] WATER-CONDITION BEFORE WELL EVACUATION (Describe):
Color: _____
Turbidity: _____
Odor: _____
Other Comments: _____

4 [ ] WELL EVACUATION:
Method: _____
Volume Removed: _____
Observations: Turbidity (clear slightly cloudy very cloudy)
Water level (rose fell no change)
Water odors: _____
Other comments: _____

Groundwater Sampling Record

Monitoring Well No. MW 64

5-4-99
Warren AFB, WY
SF-0-71

5 [ ] SAMPLE EXTRACTION METHOD:

[ ] Bailer made of: _____
[✓] Pump, type: Bennett
[ ] Other, describe: _____

Sample obtained is [X] GRAB; [ ] COMPOSITE SAMPLE

6 [ ] ON-SITE MEASUREMENTS:

Time	930AM	934 AM	938AM			Measured with
Temp (°C)	10.6	10.8	10.9			
pH	7.14	7.23	7.25			
Cond (µS/cm)	636	636	635			
DO (mg/L)	7.7	7.6	7.6			
Redox (mV)	+227.1	+243.0	+250.1			
Salinity	—	—	—			

7 [ ] SAMPLE CONTAINERS (material, number, size): _____

Check-off

1 [ ] EQUIPMENT CLEANED BEFORE USE WITH: _____
Items Cleaned (List): _____

2 [ ] PRODUCT DEPTH _____ FT. BELOW DATUM
Measured with: _____

WATER DEPTH 33.4' FT. BELOW DATUM
Measured with: Solinst

3 [ ] WATER-CONDITION BEFORE WELL EVACUATION (Describe):
Color: _____
Turbidity: _____
Odor: _____
Other Comments: _____

4 [ ] WELL EVACUATION:
Method: _____
Volume Removed: _____
Observations: Turbidity (clear slightly cloudy very cloudy)
Water level (rose fell no change)
Water odors: _____
Other comments: _____

F.E. Warren AFB
5/5/99

Groundwater Sampling Record

Monitoring Well No. 147

[ ] SAMPLE EXTRACTION METHOD:

[ ] Bailer made of: _____
[X] Pump, type: Master Flex
[ ] Other, describe: _____

Sample obtained is [X] GRAB; [ ] COMPOSITE SAMPLE

6 [ ] ON-SITE MEASUREMENTS:

Time	1136	1145	1156	1205		Measured with
Temp (°C)	10.1	9.6	9.5	9.6		YSI 30 55
pH						
Cond (µS/cm)	709	699	700	704		YSI 30
DO (mg/L)	4.10	3.88	3.81	3.80		YSI 55
Redox (mV)	92.2	98.0	101.1	101.9		Orion 250
Salinity						

6 gallons 7 gallons 8.5 gallons 9 gallons

7 [ ] SAMPLE CONTAINERS (material, number, size): _____

Check-off

1 [ ] EQUIPMENT CLEANED BEFORE USE WITH: _____
Items Cleaned (List): _____

2 [ ] PRODUCT DEPTH: _____ FT. BELOW DATUM
Measured with: _____

WATER DEPTH: 19.60 FT. BELOW DATUM
Measured with: _____

3 [ ] WATER-CONDITION BEFORE WELL EVACUATION (Describe):
Color: _____
Turbidity: _____
Odor: _____
Other Comments: _____

4 [ ] WELL EVACUATION:
Method: _____
Volume Removed: _____
Observations: Turbidity (clear slightly cloudy very cloudy)
Water level (rose fell no change)
Water odors: _____
Other comments: _____

Groundwater Sampling Record

Monitoring Well No. 196-A

5-4-99

Warren AFB, Cheyenne, Wy

5 [ ] SAMPLE EXTRACTION METHOD:

[ ] Bailer made of: _____
[ ] Pump. type: Bennett
[ ] Other, describe: _____

Sample obtained is [X] GRAB; [ ] COMPOSITE SAMPLE

6 [ ] ON-SITE MEASUREMENTS:

Time	831	835				Measured with
Temp (°C)	10.7	10.1				
pH	7.23	7.29				
Cond (µS/cm)	569	570				
DO (mg/L)	8.0	7.5				
Redox (mV)	+249.1	+253.1				
Salinity	—	—	—			

7 [ ] SAMPLE CONTAINERS (material, number, size): _____

Check-off

1 [ ] EQUIPMENT CLEANED BEFORE USE WITH: _____
Items Cleaned (List): _____

2 [ ] PRODUCT DEPTH: _____ FT. BELOW DATUM
Measured with: _____

WATER DEPTH: 36.53 ft FT. BELOW DATUM
Measured with: Solinst

3 [ ] WATER-CONDITION BEFORE WELL EVACUATION (Describe):
Color: _____
Turbidity: _____
Odor: _____
Other Comments: _____

4 [ ] WELL EVACUATION:
Method: _____
Volume Removed: _____
Observations: Turbidity (clear slightly cloudy very cloudy)
Water level (rose fell no change)
Water odors: _____
Other comments: _____

Referred to as 196 on Maps

Groundwater Sampling Record

Monitoring Well No. 196-B

5-4-99

Warren AFB- Cheyenne, Wy

5 [ ] SAMPLE EXTRACTION METHOD:

[✓] Bailer made of: Teflon

[ ] Pump, type: ~~Bladder Pump~~

[ ] Other, describe:

Sample obtained is [X] GRAB; [ ] COMPOSITE SAMPLE

6 [ ] ON-SITE MEASUREMENTS: NO Measurements Samples only

Time					Measured with
Temp (°C)					
pH					
Cond (µS/cm)					
DO (mg/L)					
Redox (mV)					
Salinity					

7 [ ] SAMPLE CONTAINERS (material, number, size):

Check-off

1 [ ] EQUIPMENT CLEANED BEFORE USE WITH:

Items Cleaned (List):

2 [ ] PRODUCT DEPTH: FT. BELOW DATUM

Measured with:

WATER DEPTH: 38.20 Ft FT. BELOW DATUM

Measured with: Sounder

3 [ ] WATER-CONDITION BEFORE WELL EVACUATION (Describe):

Color:

Turbidity:

Odor:

Other Comments:

4 [ ] WELL EVACUATION:

Method:

Volume Removed:

Observations: Turbidity (clear slightly cloudy very cloudy)

Water level (rose fell no change)

Water odors:

Other comments:

Groundwater Sampling Record

May 3, 1999
Warren AFB

Monitoring Well No. 197

5 [ ] SAMPLE EXTRACTION METHOD:

[ ] Bailer made of: _____
[ ] Pump, type: Bennett
[ ] Other, describe: _____

Sample obtained is [X] GRAB; [ ] COMPOSITE SAMPLE

6 [ ] ON-SITE MEASUREMENTS:

Time	1038	1108				Measured with
Temp (°C)	14.5	14.3				Orion 122
pH	7.42	7.47				DHA 3000
Cond (µS/cm)	842	839				Orion 122
DO (mg/L)	7.8	7.0				Orion 840
Redox (mV)	230	253				
Salinity						

7 [ ] SAMPLE CONTAINERS (material, number, size): _____

Check-off

1 [ ] EQUIPMENT CLEANED BEFORE USE WITH: _____
Items Cleaned (List): _____

2 [ ] ~~PRODUCT~~ Well DEPTH: 39.5' bgs FT. BELOW DATUM
Measured with: _____

WATER DEPTH: 33.50' TOC FT. BELOW DATUM
Measured with: Solinst

3 [ ] WATER-CONDITION BEFORE WELL EVACUATION (Describe):
Color: _____
Turbidity: _____
Odor: _____
Other Comments: _____

4 [ ] WELL EVACUATION:
Method: _____
Volume Removed: _____
Observations: Turbidity (clear slightly cloudy very cloudy)
Water level (rose fell no change)
Water odors: _____
Other comments: _____

Groundwater Sampling Record

Monitoring Well No. 190

Warren AFB. Cheyenne, Wy 5-4-99

[ ] SAMPLE EXTRACTION METHOD:

[ ] Bailer made of: _____

[ ] Pump. type: _____

[ ] Other, describe: _____

Sample obtained is [X] GRAB; [ ] COMPOSITE SAMPLE

6 [ ] ON-SITE MEASUREMENTS: water level in well very low.

Time	1437	1442				Measured with
Temp (°C)	11.7	11.7				
pH	6.92	7.23				
Cond (µS/cm)	629	629				
DO (mg/L)	0.2	1.8				
Redox (mV)	+227.6	+220.8				
Salinity	-	-				

7 [ ] SAMPLE CONTAINERS (material, number, size): _____

Check-off

1 [ ] EQUIPMENT CLEANED BEFORE USE WITH: _____

Items Cleaned (List): _____

2 [ ] PRODUCT DEPTH: _____ FT. BELOW DATUM

Measured with: _____

WATER DEPTH: 28.47 Ft FT. BELOW DATUM

Measured with: S.L. Ft

3 [ ] WATER-CONDITION BEFORE WELL EVACUATION (Describe):

Color: _____

Turbidity: _____

Odor: _____

Other Comments: _____

4 [ ] WELL EVACUATION:

Method: _____

Volume Removed: _____

Observations: Turbidity (clear slightly cloudy very cloudy)

Water level (rose fell no change)

Water odors: _____

Other comments: _____

Groundwater Sampling Record

Monitoring Well No. MW 1995 Warren AFB

5/3/99

5 [ ] SAMPLE EXTRACTION METHOD:

[ ] Bailer made of: _____
[ ] Pump, type: Master Flex
[ ] Other, describe: _____

Sample obtained is [X] GRAB; [ ] COMPOSITE SAMPLE

6 [ ] ON-SITE MEASUREMENTS:

Time	2:20	2:35	2:45			Measured with
Temp (°C)	7.7	7.1	6.8			Orion 840
pH	7.32	7.50	7.49			DAA 3000
Cond (µS/cm)	628	658	674			Orion 122
DO (mg/L)	8.2	8.1	8.1			Orion 840
Redox (mV)	224	254	267			Orion Quickcheck
Salinity						
	2 gallons	3 gallons	4 gallons			

7 [ ] SAMPLE CONTAINERS (material, number, size): _____

Check-off

1 [ ] EQUIPMENT CLEANED BEFORE USE WITH: _____
Items Cleaned (List): _____

2 [ ] PRODUCT DEPTH: NA FT. BELOW DATUM
Measured with: _____

WATER DEPTH: 10.78' TOC FT. BELOW DATUM
Measured with: Solinst

3 [ ] WATER-CONDITION BEFORE WELL EVACUATION (Describe):
Color: _____
Turbidity: _____
Odor: _____
Other Comments: _____

4 [ ] WELL EVACUATION:
Method: Master Flex Peristaltic
Volume Removed: _____
Observations: Turbidity (clear (slightly cloudy) very cloudy)
Water level (rose fell no change)
Water odors: NONE
Other comments: _____

Groundwater Sampling Record

Monitoring Well No. MW-199M

5-5-99

Warren AFB
Cheyenne, Wy

] SAMPLE EXTRACTION METHOD:

[ ] Bailer made of: _____
[X] Pump, type: Bennett
[ ] Other, describe: _____

Sample obtained is [X] GRAB; [ ] COMPOSITE SAMPLE

6 [ ] ON-SITE MEASUREMENTS:

Time	1525	1530	1535			Measured with
Temp (°C)	9.1	9.1	9.1			
pH	7.7	7.7	7.6			
Cond (µS/cm)	278	278	278			
DO (mg/L)	6.6	6.8	6.8			
Redox (mV)	+264	+266	+266			
Salinity						

7 [ ] SAMPLE CONTAINERS (material, number, size): _____

Check-off

1 [ ] EQUIPMENT CLEANED BEFORE USE WITH: _____
Items Cleaned (List): _____

2 [ ] PRODUCT DEPTH: _____ FT. BELOW DATUM
Measured with: _____

WATER DEPTH: 6.66' TOC FT. BELOW DATUM
Measured with: Solinst

3 [ ] WATER-CONDITION BEFORE WELL EVACUATION (Describe):
Color: _____
Turbidity: _____
Odor: _____
Other Comments: _____

4 [ ] WELL EVACUATION:
Method: _____
Volume Removed: _____
Observations: Turbidity (clear slightly cloudy very cloudy)
Water level (rose fell no change)
Water odors: _____
Other comments: _____

Groundwater Sampling Record

Monitoring Well No. 199D WARREN AFB 5/3/99

5 [ ] SAMPLE EXTRACTION METHOD:

[ ] Bailer made of: _____

[X] Pump, type: ~~Masterflex~~ Bennett

[ ] Other, describe: _____

Sample obtained is [X] GRAB; [ ] COMPOSITE SAMPLE

6 [ ] ON-SITE MEASUREMENTS:

						Measured with
Time	~~2:20~~	2:55	2:59	3:05		
Temp (°C)	7.7	11.9	10.5	10.5		
pH	7.32	7.47	7.44	7.4		
Cond (µS/cm)	0.278	285	283	282		
DO (mg/L)	8.2	Est. 10.0	6.5	6.5		
Redox (mV)	224	277	+269	+269		
Salinity						

10 gallons

7 [ ] SAMPLE CONTAINERS (material, number, size): _____

Check-off

1 [ ] EQUIPMENT CLEANED BEFORE USE WITH: _____

Items Cleaned (List): _____

2 [ ] PRODUCT DEPTH: _____ FT. BELOW DATUM

Measured with: _____

WATER DEPTH: 1.72' ft below PVC casing FT. BELOW DATUM

Measured with: Solinst

3 [ ] WATER-CONDITION BEFORE WELL EVACUATION (Describe):

Color: _____

Turbidity: _____

Odor: _____

Other Comments: _____

4 [ ] WELL EVACUATION:

Method: _____

Volume Removed: _____

Observations: Turbidity (clear slightly cloudy very cloudy)

Water level (rose fell no change)

Water odors: _____

Other comments: _____

Groundwater Sampling Record

Monitoring Well No. MW 201 5-4-99 Warren AFB, WY

] SAMPLE EXTRACTION METHOD:

[ ] Bailer made of: _____
[ ] Pump. type: peristaltic
[ ] Other, describe: _____

Sample obtained is [X] GRAB; [ ] COMPOSITE SAMPLE

6 [ ] ON-SITE MEASUREMENTS:

Time	1:32 PM	1:36 PM	1:40 PM			Measured with
Temp (°C)	7.8	7.8	7.8			
pH	6.96	7.12	7.16			
Cond (µS/cm)	2.73 ms	2.87 ms	2.90 ms			
DO (mg/L)	7.0	6.8	6.8			
Redox (mV)	+ 225.3	+ 237.8	+ 242.0			
Salinity	—	—	—			

7 [ ] SAMPLE CONTAINERS (material, number, size): _____

Check-off

1 [ ] EQUIPMENT CLEANED BEFORE USE WITH _____
Items Cleaned (List): _____

2 [ ] PRODUCT DEPTH: _____ FT. BELOW DATUM
Measured with: _____

WATER DEPTH: 5.94' FT. BELOW DATUM
Measured with: Solinst

3 [ ] WATER-CONDITION BEFORE WELL EVACUATION (Describe):
Color: _____
Turbidity: _____
Odor: _____
Other Comments: _____

4 [ ] WELL EVACUATION:
Method: _____
Volume Removed: _____
Observations: Turbidity (clear slightly cloudy very cloudy)
Water level (rose fell no change)
Water odors: _____
Other comments: _____

Groundwater Sampling Record

Monitoring Well No. 203

F.E. Warren AFB - LF-03
5/5/99

5 [ ] SAMPLE EXTRACTION METHOD:

[ ] Bailer made of: _____
[X] Pump, type: PERISTALTIC - MasterFlex
[ ] Other, describe: _____

Sample obtained is [X] GRAB; [ ] COMPOSITE SAMPLE

6 [ ] ON-SITE MEASUREMENTS:

Time	3:25	~~3:42~~ 3:37	3:43	3:49		Measured with
Temp (°C)	7.3	7.16	7.8	8.0		YSI 55
pH						
Cond (µS/cm)	1401	1421	1531	1537		YSI 30
DO (mg/L)	4.94	4.81	4.50	4.36		YSI 55
Redox (mV)	117.5	116.8	107.4	105.8		Orion 250A
~~Salinity~~ Volume	4 gallons	5 gallons	6 gallons	7 gallons		

7 [ ] SAMPLE CONTAINERS (material, number, size): _____

Check-off

1 [ ] EQUIPMENT CLEANED BEFORE USE WITH: _____
Items Cleaned (List): _____

2 [ ] PRODUCT DEPTH: _____ FT. BELOW DATUM
Measured with: _____

WATER DEPTH: 6.14' below PVC well casing FT. BELOW DATUM
Measured with: _____

3 [ ] WATER-CONDITION BEFORE WELL EVACUATION (Describe):
Color: clear
Turbidity: slightly
Odor: none
Other Comments: _____

4 [ ] WELL EVACUATION:
Method: _____
Volume Removed: _____
Observations: Turbidity (clear slightly cloudy very cloudy)
Water level (rose fell no change)
Water odors: _____
Other comments: _____

Groundwater Sampling Record

Monitoring Well No. 206

[ ] SAMPLE EXTRACTION METHOD:

[ ] Bailer made of: _____
[ ] Pump, type: _____
[ ] Other, describe: _____

Sample obtained is [X] GRAB; [ ] COMPOSITE SAMPLE

6 [ ] ON-SITE MEASUREMENTS:

Time	4:45	4:55	5:02			Measured with
Temp (°C)	8.4	8.4	8.3			YSI 30
pH						
Cond (µS/cm)	705	700	697			YSI 30
DO (mg/L)	5.42	5.39	5.40			YSI 55
Redox (mV)	128.4	126.5	125.5			Orion 25CA
~~Salinity~~ Volume	4 gallons	6 gallons	7 gallons			

7 [ ] SAMPLE CONTAINERS (material, number, size): _____

Check-off

1 [ ] EQUIPMENT CLEANED BEFORE USE WITH: _____
Items Cleaned (List): _____

2 [ ] PRODUCT DEPTH: _____ FT. BELOW DATUM
Measured with: _____

WATER DEPTH: 7.91' below PVC well FT. BELOW DATUM
Measured with: _____

3 [ ] WATER-CONDITION BEFORE WELL EVACUATION (Describe):
Color: _____
Turbidity: _____
Odor: _____
Other Comments: _____

4 [ ] WELL EVACUATION:
Method: _____
Volume Removed: _____
Observations: Turbidity (clear slightly cloudy very cloudy)
Water level (rose fell no change)
Water odors: _____
Other comments: _____

Groundwater Sampling Record

Monitoring Well No. 207

5-5-99
Warren AFB
Cheyenne, WY

5 [ ] SAMPLE EXTRACTION METHOD:

[ ] Bailer made of: _____
[ ] Pump. type: Bennett
[ ] Other, describe: _____

Sample obtained is [X] GRAB; [ ] COMPOSITE SAMPLE

6 [ ] ON-SITE MEASUREMENTS:

Time	1400	1405				Measured with
Temp (°C)	10.9	10.8				
pH	7.04	6.96				
Cond (µS/cm)	1130	1130				
DO (mg/L)	2.82	2.79				
Redox (mV)	+200	+201.5				
Salinity	—	—				

7 [ ] SAMPLE CONTAINERS (material, number, size): _____

Check-off

1 [ ] EQUIPMENT CLEANED BEFORE USE WITH: _____
Items Cleaned (List): _____

2 [ ] PRODUCT DEPTH: _____ FT. BELOW DATUM
Measured with: _____

WATER DEPTH: 19.70 FT. BELOW DATUM
Measured with: Sl. sl

3 [ ] WATER-CONDITION BEFORE WELL EVACUATION (Describe):
Color: _____
Turbidity: _____
Odor: _____
Other Comments: _____

4 [ ] WELL EVACUATION:
Method: _____
Volume Removed: _____
Observations: Turbidity (clear slightly cloudy very cloudy)
Water level (rose fell no change)
Water odors: _____
Other comments: _____

Groundwater Sampling Record

5-5-99

Monitoring Well No. 208

Warren AFB
Cheyenne, Wy

] SAMPLE EXTRACTION METHOD:

[ ] Bailer made of: _____
[X] Pump. type: Bennett
[ ] Other, describe: _____

Sample obtained is [X] GRAB; [ ] COMPOSITE SAMPLE

6 [ ] ON-SITE MEASUREMENTS:

Time	15:36	15:41				Measured with
Temp (°C)	10.0	9.8				
pH	6.83	6.83				
Cond (µS/cm)	1272	1271				
DO (mg/L)	1.43	1.40				
Redox (mV)	194.7	182.0				
Salinity						

7 [ ] SAMPLE CONTAINERS (material, number, size): _____

Check-off

1 [ ] EQUIPMENT CLEANED BEFORE USE WITH: _____
Items Cleaned (List): _____

2 [ ] PRODUCT DEPTH: _____ FT. BELOW DATUM
Measured with: _____

WATER DEPTH: 35.96 FT. BELOW DATUM
Measured with: Solinst

3 [ ] WATER-CONDITION BEFORE WELL EVACUATION (Describe):
Color: _____
Turbidity: _____
Odor: _____
Other Comments: _____

4 [ ] WELL EVACUATION:
Method: _____
Volume Removed: _____
Observations: Turbidity (clear slightly cloudy very cloudy)
Water level (rose fell no change)
Water odors: _____
Other comments: _____

Groundwater Sampling Record

Monitoring Well No. 209

5-5-99

Warren AFB
Cheyenne, WY

5 [ ] SAMPLE EXTRACTION METHOD:

[ ] Bailer made of: _____
[X] Pump, type: peristaltic
[ ] Other, describe: _____

Sample obtained is [X] GRAB; [ ] COMPOSITE SAMPLE

* Low water level

6 [ ] ON-SITE MEASUREMENTS:

Time	15:17	15:22				Measured with
Temp (°C)	9.5	9.2				
pH	6.82	6.87				
Cond (µS/cm)	1107	1127				
DO (mg/L)	2.13	2.08				
Redox (mV)	187.4	102.0				
Salinity						

7 [ ] SAMPLE CONTAINERS (material, number, size): _____

Check-off

1 [ ] EQUIPMENT CLEANED BEFORE USE WITH: _____
Items Cleaned (List): _____

2 [ ] PRODUCT DEPTH: _____ FT. BELOW DATUM
Measured with: _____

WATER DEPTH: 15.27 ft FT. BELOW DATUM
Measured with: Solinst

3 [ ] WATER-CONDITION BEFORE WELL EVACUATION (Describe):
Color: _____
Turbidity: _____
Odor: _____
Other Comments: _____

4 [ ] WELL EVACUATION:
Method: _____
Volume Removed: _____
Observations: Turbidity (clear slightly cloudy very cloudy)
Water level (rose fell no change)
Water odors: _____
Other comments: _____

Groundwater Sampling Record

Monitoring Well No. 209M

5-5-99
Warren AFB
Cheyenne, WY

5 [ ] SAMPLE EXTRACTION METHOD:

[ ] Bailer made of: _____
[X] Pump. type: Bennett
[ ] Other, describe: _____

Sample obtained is [X] GRAB; [ ] COMPOSITE SAMPLE

6 [ ] ON-SITE MEASUREMENTS:

Time	14:30	14:35				Measured with
Temp (°C)	10.7	10.8				
pH	7.07	6.98				
Cond (µS/cm)	1023	1028				
DO (mg/L)	1.11	1.04				
Redox (mV)	200.4	263.9				
Salinity						

7 [ ] SAMPLE CONTAINERS (material, number, size): _____

Check-off

1 [ ] EQUIPMENT CLEANED BEFORE USE WITH: _____
Items Cleaned (List): _____

2 [ ] PRODUCT DEPTH: _____ FT. BELOW DATUM
Measured with: _____

WATER DEPTH: 16.90 ft FT. BELOW DATUM
Measured with: Solinst

3 [ ] WATER-CONDITION BEFORE WELL EVACUATION (Describe):
Color: _____
Turbidity: _____
Odor: _____
Other Comments: _____

4 [ ] WELL EVACUATION:
Method: _____
Volume Removed: _____
Observations: Turbidity (clear slightly cloudy very cloudy)
Water level (rose fell no change)
Water odors: _____
Other comments: _____

Groundwater Sampling Record

Monitoring Well No. 209D

5-5-99
Warren AFB
Cheyenne, Wy

5 [ ] SAMPLE EXTRACTION METHOD:

[ ] Bailer made of: _____
[X] Pump, type: Bennett
[ ] Other, describe: _____

Sample obtained is [X] GRAB; [ ] COMPOSITE SAMPLE

6 [ ] ON-SITE MEASUREMENTS:

Time	325 PM	330	~~335~~			Measured with
Temp (°C)	9.9	10.1				
pH	7.36	7.53				
Cond (µS/cm)	312	312				
DO (mg/L)	2.85	2.79				
Redox (mV)	+228.7	+231.1				
Salinity	—	—	—			

7 [ ] SAMPLE CONTAINERS (material, number, size): _____

Check-off

1 [ ] EQUIPMENT CLEANED BEFORE USE WITH: _____
Items Cleaned (List): _____

2 [ ] PRODUCT DEPTH: _____ FT. BELOW DATUM
Measured with: _____

WATER DEPTH: 16.19 ~ D FT. BELOW DATUM
Measured with: Solinst

3 [ ] WATER-CONDITION BEFORE WELL EVACUATION (Describe):
Color: _____
Turbidity: _____
Odor: _____
Other Comments: _____

4 [ ] WELL EVACUATION:
Method: _____
Volume Removed: _____
Observations: Turbidity (clear slightly cloudy very cloudy)
Water level (rose fell no change)
Water odors: _____
Other comments: _____

Groundwater Sampling Record
Monitoring Well No. MW 210

Warren AFB; WY
5-5-99

] SAMPLE EXTRACTION METHOD:

[ ] Bailer made of:
[✓] Pump, type: Peristaltic
[ ] Other, describe:

*low level in well

Sample obtained is [X] GRAB; [ ] COMPOSITE SAMPLE

~~*no on-site measurements possible~~
RPK 5-5-99

6 [ ] ON-SITE MEASUREMENTS:

Time	1104	1109				Measured with
Temp (°C)	9.3	9.3				
pH	7.2	7.12				
Cond (µS/cm)	970	969				
DO (mg/L)	1.9	1.9				
Redox (mV)	+268	+266				
Salinity	—	—				

7 [ ] SAMPLE CONTAINERS (material, number, size):

Check-off

1 [ ] EQUIPMENT CLEANED BEFORE USE WITH
Items Cleaned (List):

2 [ ] PRODUCT DEPTH FT. BELOW DATUM
Measured with:

WATER DEPTH 13.60' FT. BELOW DATUM
Measured with: Solinst

3 [ ] WATER-CONDITION BEFORE WELL EVACUATION (Describe):
Color:
Turbidity:
Odor:
Other Comments:

4 [ ] WELL EVACUATION:
Method:
Volume Removed:
Observations: Turbidity (clear slightly cloudy very cloudy)
Water level (rose fell no change)
Water odors:
Other comments:

Groundwater Sampling Record

Monitoring Well No. MW-210M

5-5-99

Warren AFB, Cheyenne, WY

5 [ ] SAMPLE EXTRACTION METHOD:

[ ] Bailer made of: _____
[ ] Pump, type: Bennett
[ ] Other, describe: _____

Sample obtained is [X] GRAB; [ ] COMPOSITE SAMPLE

6 [ ] ON-SITE MEASUREMENTS:

Time	1034	1039				Measured with:
Temp (°C)	11.3	11.0				
pH	7.47	7.45				
Cond (µS/cm)	443	443				
DO (mg/L)	2.51	2.67				
Redox (mV)	+206.8	+213.6				
Salinity	–	–				

7 [ ] SAMPLE CONTAINERS (material, number, size): _____

Check-off

1 [ ] EQUIPMENT CLEANED BEFORE USE WITH: _____
Items Cleaned (List): _____

2 [ ] PRODUCT DEPTH: _____ FT. BELOW DATUM
Measured with: _____

WATER DEPTH: 14.70' FT. BELOW DATUM
Measured with: Solinst

3 [ ] WATER-CONDITION BEFORE WELL EVACUATION (Describe):
Color: _____
Turbidity: _____
Odor: _____
Other Comments: _____

4 [ ] WELL EVACUATION:
Method: _____
Volume Removed: _____
Observations: Turbidity (clear slightly cloudy very cloudy)
Water level (rose fell no change)
Water odors: _____
Other comments: _____

Groundwater Sampling Record

Monitoring Well No. MW 2107

5-5-99

Warren AFB, Cheyenne, WY

5 [ ] SAMPLE EXTRACTION METHOD:

[ ] Bailer made of: _____

[X] Pump, type: Bennett

[ ] Other, describe: _____

Sample obtained is [X] GRAB; [ ] COMPOSITE SAMPLE

6 [ ] ON-SITE MEASUREMENTS:

Time	1115AM	1120AM	1125AM			Measured with
Temp (°C)	10.5	10.5	10.5			
pH	7.41	7.38	7.37			
Cond (µS/cm)	481	430	415			
DO (mg/L)	1.60	1.43	1.35			
Redox (mV)	+269	+274	+276			
Salinity	—	—	—			

7 [ ] SAMPLE CONTAINERS (material, number, size): _____

Check-off

1 [ ] EQUIPMENT CLEANED BEFORE USE WITH _____

Items Cleaned (List): _____

2 [ ] PRODUCT DEPTH: _____ FT. BELOW DATUM

Measured with: _____

WATER DEPTH: 17.60' FT. BELOW DATUM

Measured with: Solinst

3 [ ] WATER-CONDITION BEFORE WELL EVACUATION (Describe):

Color: _____

Turbidity: _____

Odor: _____

Other Comments: _____

4 [ ] WELL EVACUATION:

Method: _____

Volume Removed: _____

Observations: Turbidity (clear slightly cloudy very cloudy)

Water level (rose fell no change)

Water odors: _____

Other comments: _____

Groundwater Sampling Record

Monitoring Well No. MW211

Warren AFB, WY
5-4-99

5 [ ] SAMPLE EXTRACTION METHOD:

[ ] Bailer made of: _____
[A] Pump, type: Marker Max
[ ] Other, describe: _____

Sample obtained is [X] GRAB; [ ] COMPOSITE SAMPLE

6 [ ] ON-SITE MEASUREMENTS:

Time	1010	1018				Measured with
Temp (°C)	9.5	9.1				YSI 30
pH	NO PH	Meter				
Cond (µS/cm)	695	694				YSI 30
DO (mg/L)	4.31	4.33				YSI 55
Redox (mV)	128.8	120.4				Orion 250
Salinity						

5 gal.

7 [ ] SAMPLE CONTAINERS (material, number, size): _____

Check-off

1 [ ] EQUIPMENT CLEANED BEFORE USE WITH: _____
Items Cleaned (List): _____

2 [ ] PRODUCT DEPTH: NA FT. BELOW DATUM
Measured with: _____

WATER DEPTH: 16.0 ft FT. BELOW DATUM
Measured with: Solinist

3 [ ] WATER-CONDITION BEFORE WELL EVACUATION (Describe):
Color: _____
Turbidity: _____
Odor: _____
Other Comments: _____

4 [ ] WELL EVACUATION:
Method: _____
Volume Removed: _____
Observations: Turbidity (clear slightly cloudy very cloudy)
Water level (rose fell no change)
Water odors: _____
Other comments: _____

Groundwater Sampling Record Warren AFB
Monitoring Well No. MW-232 5/3/99

] SAMPLE EXTRACTION METHOD:

[ ] Bailer made of: _____
[ ] Pump, type: Masterflex
[ ] Other, describe: _____

Sample obtained is [X] GRAB; [ ] COMPOSITE SAMPLE

6 [ ] ON-SITE MEASUREMENTS:

Time	1220	1225	1230			Measured with
Temp (°C)	8.5	8.7	8.8			
pH	7.6	7.3	7.3			
Cond (µS/cm)	750	752	754			
DO (mg/L)	6.2	6.0	6.0			
Redox (mV)	+222	+244	+260			
Salinity						

ORP = +210

7 [ ] SAMPLE CONTAINERS (material, number, size): _____

Check-off

1 [ ] EQUIPMENT CLEANED BEFORE USE WITH: _____
Items Cleaned (List): _____

2 [ ] ~~PRODUCT~~ well DEPTH: 20' FT. BELOW DATUM
Measured with: _____

WATER DEPTH: 7.12' TOC FT. BELOW DATUM
Measured with: Solinst

3 [ ] WATER-CONDITION BEFORE WELL EVACUATION (Describe):
Color: _____
Turbidity: _____
Odor: _____
Other Comments: _____

4 [ ] WELL EVACUATION:
Method: _____
Volume Removed: _____
Observations: Turbidity (clear slightly cloudy very cloudy)
Water level (rose fell no change)
Water odors: _____
Other comments: _____

Groundwater Sampling Record

Monitoring Well No. 233

5-4-99
Warren AFB, WY

5 [ ] SAMPLE EXTRACTION METHOD:

[ ] Bailer made of: _____
[✓] Pump, type: Bennett
[ ] Other, describe: _____

Sample obtained is [X] GRAB; [ ] COMPOSITE SAMPLE

6 [ ] ON-SITE MEASUREMENTS:

Time	1029	1033	1037			Measured with
Temp (°C)	11.1	11.2	11.9			
pH	7.65	7.28	7.28			
Cond (µS/cm)	754	713	698			
DO (mg/L)	7.5	7.5	7.3			
Redox (mV)	+233.0	+244.0	+250.2			
Salinity	—	—	—			

7 [ ] SAMPLE CONTAINERS (material, number, size): _____

Check-off

1 [ ] EQUIPMENT CLEANED BEFORE USE WITH: _____
Items Cleaned (List): _____

2 [ ] PRODUCT DEPTH: _____ FT. BELOW DATUM
Measured with: _____

WATER DEPTH: 33.75' FT. BELOW DATUM
Measured with: Solinst

3 [ ] WATER-CONDITION BEFORE WELL EVACUATION (Describe):
Color: _____
Turbidity: _____
Odor: _____
Other Comments: _____

4 [ ] WELL EVACUATION:
Method: _____
Volume Removed: _____
Observations: Turbidity (clear slightly cloudy very cloudy)
Water level (rose fell no change)
Water odors: _____
Other comments: _____

Groundwater Sampling Record

Monitoring Well No. 230 F.E. Warren AFB

5/4/99

] SAMPLE EXTRACTION METHOD:

[ ] Bailer made of: _____

[X] Pump, type: Master Flex

[ ] Other, describe: _____

Sample obtained is [X] GRAB; [ ] COMPOSITE SAMPLE

6 [ ] ON-SITE MEASUREMENTS:

Time	3:30	3:35	3:40			Measured with
Temp (°C)	9.8	9.8	9.6			YSI 55
pH						
Cond (µS/cm)	1599	1597	1598			YSI 30
DO (mg/L)	6.01	4.16	5.45			YSI 55
Redox (mV)	97.9	96.8	94.2			Orion 250A
Salinity						

3 gallons 3.25 gallons 4 gal

7 [ ] SAMPLE CONTAINERS (material, number, size): _____

Check-off

1 [ ] EQUIPMENT CLEANED BEFORE USE WITH: _____

Items Cleaned (List): _____

2 [ ] PRODUCT DEPTH: _____ FT. BELOW DATUM

Measured with: _____

WATER DEPTH: 17.60 ft below PVC casing FT. BELOW DATUM

Measured with: _____

3 [ ] WATER-CONDITION BEFORE WELL EVACUATION (Describe):

Color: _____

Turbidity: _____

Odor: _____

Other Comments: _____

4 [ ] WELL EVACUATION:

Method: _____

Volume Removed: _____

Observations: Turbidity (clear slightly cloudy very cloudy)

Water level (rose fell no change)

Water odors: _____

Other comments: _____

Groundwater Sampling Record
Monitoring Well No. MW 237 Warren AFB WY
5-4-99

5 [ ] SAMPLE EXTRACTION METHOD:

[ ] Bailer made of: _____
[X] Pump, type: peristaltic
[ ] Other, describe: _____

Sample obtained is [X] GRAB; [ ] COMPOSITE SAMPLE

6 [ ] ON-SITE MEASUREMENTS:

Time	1328	1333	1338			Measured with
Temp (°C)	7.3	7.5	7.5			
pH	6.54	7.22	7.40			
Cond (µS/cm)	955	956	955			
DO (mg/L)	1.4	1.5	1.6			
Redox (mV)	+215.1	+225.9	+259.9			
Salinity	—	—	—			

7 [ ] SAMPLE CONTAINERS (material, number, size): _____

Check-off

1 [ ] EQUIPMENT CLEANED BEFORE USE WITH: _____
Items Cleaned (List): _____

2 [ ] PRODUCT DEPTH: _____ FT. BELOW DATUM
Measured with: _____

WATER DEPTH: 4.6' FT. BELOW DATUM
Measured with: Solinst

3 [ ] WATER-CONDITION BEFORE WELL EVACUATION (Describe):
Color: _____
Turbidity: _____
Odor: _____
Other Comments: _____

4 [ ] WELL EVACUATION:
Method: _____
Volume Removed: _____
Observations: Turbidity (clear slightly cloudy very cloudy)
Water level (rose fell no change)
Water odors: _____
Other comments: _____

Warren AFB, Wy
5-4-99

Groundwater Sampling Record

Monitoring Well No. MW 238

[ ] SAMPLE EXTRACTION METHOD:

[ ] Bailer made of: _____
[ ] Pump. type: Peristaltic
[ ] Other, describe: _____

Sample obtained is [X] GRAB; [ ] COMPOSITE SAMPLE

6 [ ] ON-SITE MEASUREMENTS:

Time	235 PM	240	245			Measured with
Temp (°C)	9.1	8.8	8.8			
pH	7.52	7.06	7.07			
Cond (µS/cm)	1.46ms	1.46ms	1.47ms			
DO (mg/L)	4.0	3.7	4.1			
Redox (mV)	+231.6	+241.6	250.8			
Salinity	—	—	—			

7 [ ] SAMPLE CONTAINERS (material, number, size): _____

Check-off

1 [ ] EQUIPMENT CLEANED BEFORE USE WITH: _____
Items Cleaned (List): _____

2 [ ] PRODUCT DEPTH: _____ FT. BELOW DATUM
Measured with: _____

WATER DEPTH: 8.90' FT. BELOW DATUM
Measured with: Solinst

3 [ ] WATER-CONDITION BEFORE WELL EVACUATION (Describe):
Color: _____
Turbidity: _____
Odor: _____
Other Comments: _____

4 [ ] WELL EVACUATION:
Method: _____
Volume Removed: _____
Observations: Turbidity (clear slightly cloudy very cloudy)
Water level (rose fell no change)
Water odors: _____
Other comments: _____

Groundwater Sampling Record

Monitoring Well No. PES-15

5-6-99
Warren AFB
Cheyenne, WY

5 [ ] SAMPLE EXTRACTION METHOD:

[ ] Bailer made of: _____
[X] Pump, type: Bennett
[ ] Other, describe: _____

Sample obtained is [X] GRAB; [ ] COMPOSITE SAMPLE

6 [ ] ON-SITE MEASUREMENTS:

Time	1010	1014	1020			Measured with:
Temp (°C)	10.3	10.4	10.5			
pH	7.09	7.13	7.15			
Cond (µS/cm)	1182	1181	1178			
DO (mg/L)	1.17	1.07	1.10			
Redox (mV)	+103	+68.4	58.9			
Salinity	—	—	—			

7 [ ] SAMPLE CONTAINERS (material, number, size): _____

Check-off

1 [ ] EQUIPMENT CLEANED BEFORE USE WITH: _____
Items Cleaned (List): _____

2 [ ] PRODUCT DEPTH _____ FT. BELOW DATUM
Measured with: _____

WATER DEPTH: 28.88 FT. BELOW DATUM
Measured with: Solinst

3 [ ] WATER-CONDITION BEFORE WELL EVACUATION (Describe):
Color: _____
Turbidity: _____
Odor: _____
Other Comments: _____

4 [ ] WELL EVACUATION:
Method: _____
Volume Removed: _____
Observations: Turbidity (clear slightly cloudy very cloudy)
Water level (rose fell no change)
Water odors: _____
Other comments: _____

Groundwater Sampling Record

Monitoring Well No. PES-2D 5-6-99

Warren AFB, WY

[ ] SAMPLE EXTRACTION METHOD:

[ ] Bailer made of: _____
[ ] Pump, type: Bennett
[ ] Other, describe: _____

Sample obtained is [X] GRAB; [ ] COMPOSITE SAMPLE

6 [ ] ON-SITE MEASUREMENTS: Pump depth @ 35' due to MuO. Cannot sample close to bottom of well.

Time	915	920	925			Measured with
Temp (°C)	9.5	9.6	9.8			
pH	6.92	7.23	7.25			
Cond (µS/cm)	826	825	825			
DO (mg/L)	1.79	1.96	1.97			
Redox (mV)	+184.0	+184.1	186.4			
Salinity	—	—				

7 [ ] SAMPLE CONTAINERS (material, number, size): _____

Check-off

1 [ ] EQUIPMENT CLEANED BEFORE USE WITH: _____
Items Cleaned (List): _____

2 [ ] PRODUCT DEPTH: _____ FT. BELOW DATUM
Measured with: _____

WATER DEPTH: 20.75 FT. BELOW DATUM
Measured with: Solinst

3 [ ] WATER-CONDITION BEFORE WELL EVACUATION (Describe):
Color: _____
Turbidity: _____
Odor: _____
Other Comments: _____

4 [ ] WELL EVACUATION:
Method: _____
Volume Removed: _____
Observations: Turbidity (clear slightly cloudy very cloudy)
Water level (rose fell no change)
Water odors: _____
Other comments: _____

Groundwater Sampling Record

Monitoring Well No. PES-3D Warren AFB WY 5-6-95

5 [ ] SAMPLE EXTRACTION METHOD:

[ ] Bailer made of: _____
[X] Pump, type: White-Flex peristaltic
[ ] Other, describe: _____

Sample obtained is [X] GRAB; [ ] COMPOSITE SAMPLE

6 [ ] ON-SITE MEASUREMENTS:

Time	1020	1027				Measured with
Temp (°C)	10.0	10.3				
pH						
Cond (µS/cm)	4074	4066.7				
DO (mg/L)	5.16	4.85				
Redox (mV)	149.6	145.2				
~~Salinity~~ Vol	2 gallons	2.5 gal				

7 [ ] ~~SAMPLE CONTAINERS (material, number, size)~~ Comments: During development well continually went dry and lots of silt @ bottom of well. Purging unachievable because well is not fully developed

Check-off

1 [ ] EQUIPMENT CLEANED BEFORE USE WITH: _____
Items Cleaned (List): _____

2 [ ] PRODUCT DEPTH: NA FT. BELOW DATUM
Measured with: _____

WATER DEPTH: 17.5 ft below PVC well FT. BELOW DATUM
Measured with: _____

3 [ ] WATER-CONDITION BEFORE WELL EVACUATION (Describe):
Color: _____
Turbidity: _____
Odor: _____
Other Comments: _____

4 [ ] WELL EVACUATION:
Method: _____
Volume Removed: _____
Observations: Turbidity (clear slightly cloudy very cloudy)
Water level (rose fell no change)
Water odors: _____
Other comments: _____

Groundwater Sampling Record

Monitoring Well No. PES-4D

Warren AFB WY
5-5-99

[ ] SAMPLE EXTRACTION METHOD:

[ ] Bailer made of: _____
[ ] Pump, type: Bennett
[ ] Other, describe: _____

Sample obtained is [X] GRAB; [ ] COMPOSITE SAMPLE

6 [ ] ON-SITE MEASUREMENTS:

Time	11:34 PM	1:39 PM				Measured with
Temp (°C)	11.4	11.2				
pH	7.81	7.91				
Cond (µS/cm)	406	406				
DO (mg/L)	2.07	2.03				
Redox (mV)	+171.0	+140.0				
Salinity	—	—				

7 [ ] SAMPLE CONTAINERS (material, number, size): _____

Check-off

1 [ ] EQUIPMENT CLEANED BEFORE USE WITH: _____
Items Cleaned (List): _____

2 [ ] PRODUCT DEPTH: _____ FT. BELOW DATUM
Measured with: _____

WATER DEPTH: 18.58 ft FT. BELOW DATUM
Measured with: solinst

3 [ ] WATER-CONDITION BEFORE WELL EVACUATION (Describe):
Color: _____
Turbidity: _____
Odor: _____
Other Comments: _____

4 [ ] WELL EVACUATION:
Method: _____
Volume Removed: _____
Observations: Turbidity (clear slightly cloudy very cloudy)
Water level (rose fell no change)
Water odors: _____
Other comments: _____

Groundwater Sampling Record
Monitoring Well No. PES-5D

Warren AFB, WY
5-6-99

5 [ ] SAMPLE EXTRACTION METHOD:

[ ] Bailer made of: _____
[X] Pump, type: MasterFlex
[ ] Other, describe: _____

Sample obtained is [X] GRAB; [ ] COMPOSITE SAMPLE

6 [ ] ON-SITE MEASUREMENTS:

Time	1115	1123	1132	1137		Measured with:
Temp (°C)	13.1	12.5	12.2	12.2		YSI 30
pH						
Cond (µS/cm)	1149	1151	1152	1160		YSI 30
DO (mg/L)	4.03	4.31	3.50	4.07		YSI 55
Redox (mV)	130.5	125.5	126.8	120.6		Orion 250A
~~Salinity~~ Volume	2 gallons	2.5 gallons	3.0 gal.	3.5 gal.		

7 [ ] SAMPLE CONTAINERS (material, number, size): _____

Check-off

1 [ ] EQUIPMENT CLEANED BEFORE USE WITH: _____
Items Cleaned (List): _____

2 [ ] PRODUCT DEPTH: _____ FT. BELOW DATUM
Measured with: _____

WATER DEPTH: 7.3 ft below PVC well FT. BELOW DATUM
Measured with: _____

3 [ ] WATER-CONDITION BEFORE WELL EVACUATION (Describe):
Color: _____
Turbidity: _____
Odor: _____
Other Comments: _____

4 [ ] WELL EVACUATION:
Method: _____
Volume Removed: _____
Observations: Turbidity (clear slightly cloudy very cloudy)
Water level (rose fell no change)
Water odors: _____
Other comments: _____

Groundwater Sampling Record

Monitoring Well No. PES-6D

5-6-99
Warren AFB

] SAMPLE EXTRACTION METHOD:

[ ] Bailer made of: _____
[ ] Pump, type: _____
[ ] Other, describe: _____

Sample obtained is [X] GRAB; [ ] COMPOSITE SAMPLE * Low water level

6 [ ] ON-SITE MEASUREMENTS:

Time	11:02					Measured with
Temp (°C)	10.6					
pH	8.14					
Cond (µS/cm)	317					
DO (mg/L)	3.48					
Redox (mV)	137.1					
Salinity						

7 [ ] SAMPLE CONTAINERS (material, number, size): _____

Check-off

1 [ ] EQUIPMENT CLEANED BEFORE USE WITH _____
Items Cleaned (List): _____

2 [ ] PRODUCT DEPTH _____ FT. BELOW DATUM
Measured with: _____

WATER DEPTH 22.45 ft FT. BELOW DATUM
Measured with: Solinst

3 [ ] WATER-CONDITION BEFORE WELL EVACUATION (Describe):
Color: _____
Turbidity: _____
Odor: _____
Other Comments: _____

4 [ ] WELL EVACUATION:
Method: _____
Volume Removed: _____
Observations: Turbidity (clear slightly cloudy very cloudy)
Water level (rose fell no change)
Water odors: _____
Other comments: _____

Groundwater Sampling Record

Monitoring Well No. PSE-6d

5-5-99

Warren AFB, Cheyenne, Wy

5 [ ] SAMPLE EXTRACTION METHOD:

[ ] Bailer made of: _____

[ ] Pump, type: _____

[ ] Other, describe: _____

Sample obtained is [X] GRAB; [ ] COMPOSITE SAMPLE

Re-measured on 5-6-99

* Newly installed well
- Water level low -
- No measurements possible -
- Purged 4 gallons
- no samples taken

6 [ ] ON-SITE MEASUREMENTS:

Time						Measured with
Temp (°C)						
pH						
Cond (µS/cm)						
DO (mg/L)						
Redox (mV)						
Salinity						

7 [ ] SAMPLE CONTAINERS (material, number, size): _____

Check-off

1 [ ] EQUIPMENT CLEANED BEFORE USE WITH: _____

Items Cleaned (List): _____

2 [ ] PRODUCT DEPTH: _____ FT. BELOW DATUM

Measured with: _____

22.45

WATER DEPTH: 26.50 ft FT. BELOW DATUM

Measured with: Solinst

3 [ ] WATER-CONDITION BEFORE WELL EVACUATION (Describe):

Color: _____

Turbidity: _____

Odor: _____

Other Comments: _____

4 [ ] WELL EVACUATION:

Method: _____

Volume Removed: _____

Observations: Turbidity (clear slightly cloudy very cloudy)

Water level (rose fell no change)

Water odors: _____

Other comments: _____

Groundwater Sampling Record

Monitoring Well No. BE-63

5-5-99

Warren AFB, Cheyenne, WY

] SAMPLE EXTRACTION METHOD:

[ ] Bailer made of: _____

[ ] Pump, type: Peristaltic

[ ] Other, describe: _____

Sample obtained is [X] GRAB; [ ] COMPOSITE SAMPLE

6 [ ] ON-SITE MEASUREMENTS:

Time	09:15	9:20	09:25			Measured with
Temp (°C)	9.1	9.1	9.1			
pH	7.38	7.41	7.42			
Cond (µS/cm)	551	549	547			
DO (mg/L)	2.76	2.63	2.61			
Redox (mV)	+141.8	+39.0	+29.9			
Salinity	–	–	–			

7 [ ] SAMPLE CONTAINERS (material, number, size): _____

Check-off

1 [ ] EQUIPMENT CLEANED BEFORE USE WITH: _____

Items Cleaned (List): _____

2 [ ] PRODUCT DEPTH: _____ FT. BELOW DATUM

Measured with: _____

WATER DEPTH: 12.90 ft FT. BELOW DATUM

Measured with: Solinst

3 [ ] WATER-CONDITION BEFORE WELL EVACUATION (Describe):

Color: _____

Turbidity: _____

Odor: _____

Other Comments: _____

4 [ ] WELL EVACUATION:

Method: _____

Volume Removed: _____

Observations: Turbidity (clear slightly cloudy very cloudy)

Water level (rose fell no change)

Water odors: _____

Other comments: _____

ROBERT S. KERR
ENVIRONMENTAL
RESEARCH LABORATORY
ADA, OKLAHOMA

COPY 36

UNITED STATES
ENVIRONMENTAL PROTECTION AGENCY

SOURCE Warren AFB, WY DATE 5-5-99

ANALYSIS Water Quality GROUP _____ ANALYST MB

SAMPLE	TIME	Fe^{+2}	ALK.	CO_2	$S^{=}$			
MW-210M	1044	<.1	120	25	<.1			
MW-210D	1051	<.1	180	25	<.1			
MW-210D	1126	<.1	120	20	<.1			
MW-147	1207	<.1	200	35	<.1	pH = 7.31		
PZ-5-D	1335	<.1	160	15	<.1			
MW-209M	1435	<.1	200	25	<.1			
MW-209	1510	<.1	240	30	<.1			
MW-209D	1533	<.1	180	30	<.1			
MW-207	1605	<.1	200	40	<.1			
MW-203	1700	<.1	200	40	<.1	pH = 7.33		
MW-208	1742	<.1	240	35	<.1			
MW 206	1830	<.1	180	20	<.1	pH = 6.96		

REMARKS _____

ROBERT S. KERR
ENVIRONMENTAL
RESEARCH LABORATORY
ADA, OKLAHOMA

UNITED STATES
ENVIRONMENTAL PROTECTION AGENCY

SOURCE Warren AFB DATE 5/3/99

ANALYSIS Water Quality GROUP all mg/L ANALYST PJ2

SAMPLE	TIME	Fe^{++}	Alk	CO_2	$S^=$			
MW-197	11:15	<.1	220	25	<.1			
MW-232	13:10	<.1	220	25	<.1			
MW-199S	14:05	<.1	200	10	<.1			
MW-199M	14:55	<.1	140	10	<.1			
MW-199D	15:45	<.1	120	10	<.1			
	5/4/99							
MW-196A	0815	<.1	140	15	<.1			
196 = MW-196B	0930	<.1	120	15	<.1			
MW-64	0945	<.1	200	20	<.1			
MW-233	1035	<.1	140	15	<.1			
MW-201	1340	<.1	286	25	<.1			
MW-238	1420	<.1	300	25	<.1	pH = 7.32		
MW-236	1440	<.1	220	25	<.1			
MW-237	1530	<.1	240	20	<.1			
MW-198	1630	<.1	220	15	<.1			
5-5-99 → MW-211	1645	<.1	200	25				
5-5-99 MW PES 65	9:24	<.1	160	30	<.1			

REMARKS

ROBERT S. KERR
ENVIRONMENTAL
RESEARCH LABORATORY
ADA, OKLAHOMA

COPY 37

UNITED STATES
ENVIRONMENTAL PROTECTION AGENCY

SOURCE Warren AFB DATE 5/6/99

ANALYSIS Water Quality GROUP Nat. atten ANALYST

SAMPLE	TIME	Fe^{+2}	ALK	CO_2	$S^=$			
MW-62	930	<.1	160	25	<.1			
PES-2D	936	<.1	240	35	<.1			
PES-1S	1020	<.1	220	40	<.1			
PES-3D	1049	<.1	140	40	<.1	P^{tt} = 1.09		
PES-6D	1105	<.1	120	30	<.1	pH = 7.18		
PES-5D	1149	<.1	140	40	<.1			

REMARKS

Client: **F.E. Warren**

Project:

Project No.:

Well No.: **PES-1S**

Test Date: **May 7, 1999**

Formation Tested:

Rising (R) or Falling (F) Head Test: **Falling-1st Test**

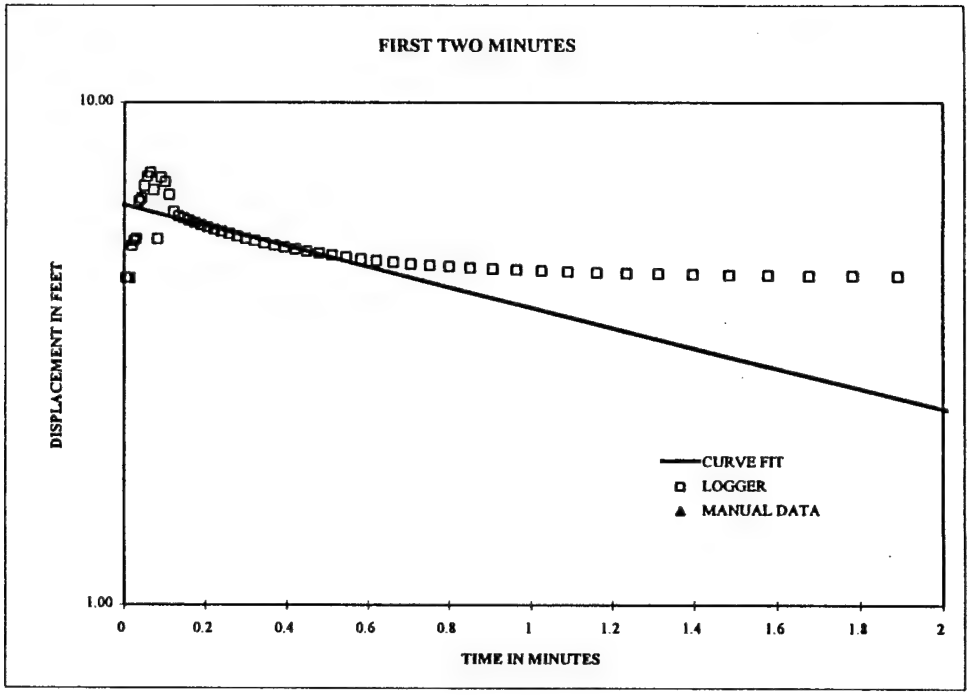
Logger Data File:

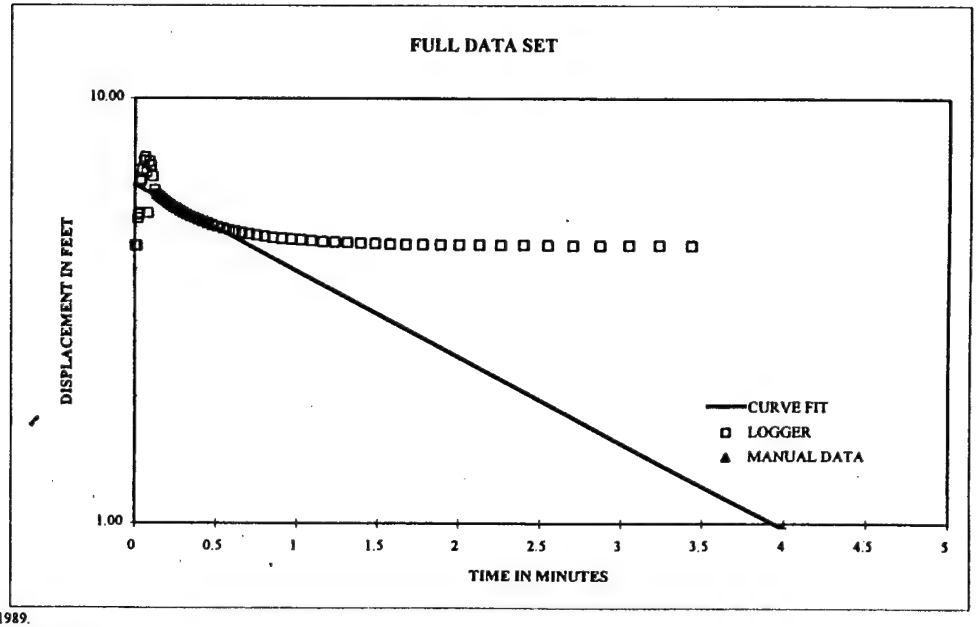
Hydraulic conductivity	1.16E-03	cm/sec
	2.28E-03	ft/min
	3.29	ft/day

Casing stickup	1.49	feet
Static water level (from top of casing)	28.88	feet
Depth to bottom of screen (from ground level)	37.51	feet
Boring diameter	8.25	inches
Casing diameter	2.00	inches
Screen diameter	2.00	inches
Screen length	10.00	feet
Depth to "impermeable boundary"	50.00	feet
Porosity of filter pack	0.20	
Slug diameter (optional)		inches
Slug length (optional)		feet
Theoretical ΔH at time zero (Y_0)	0.00	feet
Actual ΔH at time zero (Y_0)	6.300	feet
ΔH at time t (Y_t)	0.150	feet
Time	8.00	min

Bouwer-Rice Parameters

feet	cm		cm	
27.39	834.85	*SW*		
10.12	308.46	*H*	120.00	*L/Rw*
27.51	838.50	*Ts*	0.45	*H/D*
0.083	2.54	*Rw*	4.60	*A*
0.171	5.21	*Rc*	0.75	*B*
0.167	5.08	*DS*	4.60	*C*
10.00	304.80	*L*	5.01	*Ln[(D-H)/Rw]'*
22.61	689.15	*D*	5.01	*Ln[(D-H)/Rw]*
6.30000006	192.02	Y_e	3.35	equation (8)
0.15	4.57	Y_t	3.74	equation (9)
	480.00	*t (seconds)*	3.35	*Ln(Re/Rw)*
	0.20	*n*	1.2E-03	equation (6)





Bouwer, Herman. 1989. "The Bouwer and Rice Slug Test - An Update". Ground Water vol. 27, no. 3, May-June 1989.

Bouwer, H. and R.C. Rice. 1976. A Slug Test for Determining Hydraulic Conductivity of Unconfined Aquifers With Completely or Partially Penetrating Wells". Water Resources Research. vol 12, no. 3, June 1976.

Client: **F.E. Warren**

Project:

Project No.:

Well No.: **PES-1S**

Test Date: **May 7, 1999**

Formation Tested:

Rising (R) or Falling (F) Head Test: **Rising - 1st test**

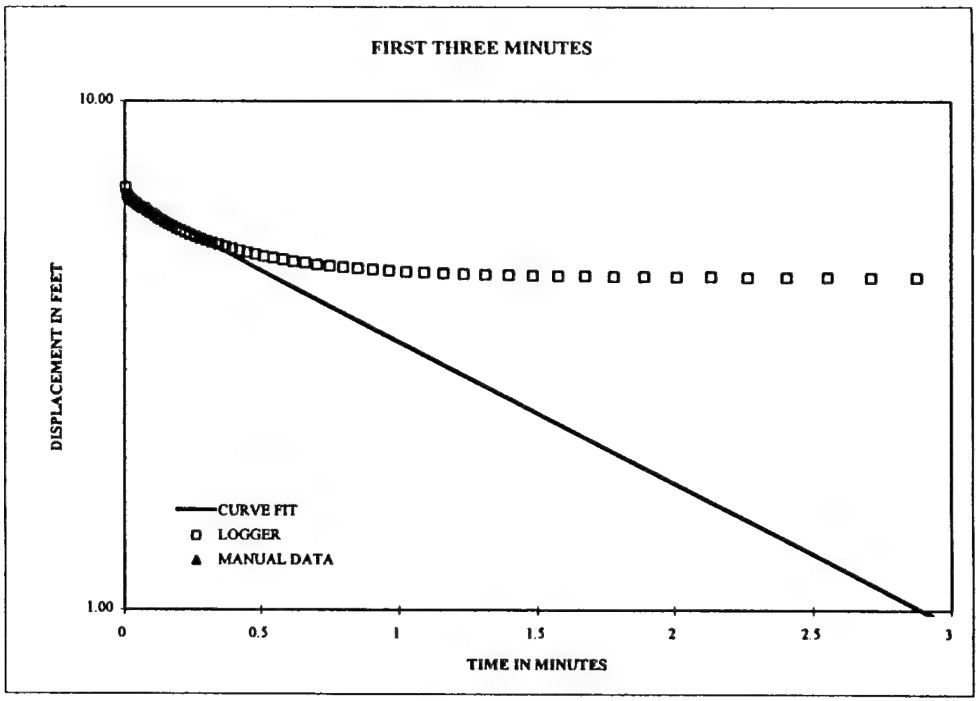
Logger Data File:

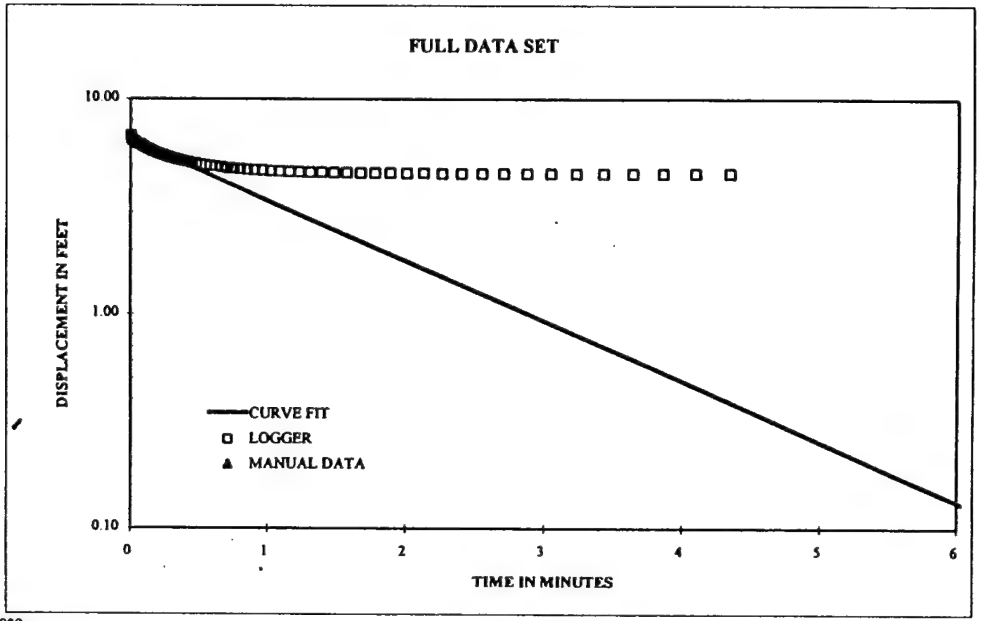
Hydraulic conductivity **1.61E-03 cm/sec**
3.16E-03 ft/min
4.55 ft/day

Casing stickup	1.49	feet
Static water level (from top of casing)	28.88	feet
Depth to bottom of screen (from ground level)	37.51	feet
Boring diameter	8.25	inches
Casing diameter	2.00	inches
Screen diameter	2.00	inches
Screen length	10.00	feet
Depth to "impermeable boundary"	50.00	feet
Porosity of filter pack	0.20	
Slug diameter (optional)		inches
Slug length (optional)		feet
Theoretical ΔH at time zero (Y_0)	0.00	feet
Actual ΔH at time zero (Y_0)	6.500	feet
ΔH at time t (Y_t)	0.010	feet
Time	10.00	min

Bouwer-Rice Parameters

feet	cm		cm	
27.39	834.85	*SW*		
10.12	308.46	*H*	120.00	*L/Rw*
27.51	838.50	*Ts*	0.45	*H/D*
0.083	2.54	*Rw*	4.60	*A*
0.171	5.21	*Rc*	0.75	*B*
0.167	5.08	*DS*	4.60	*C*
10.00	304.80	*L*	5.01	*Ln[(D-H)/Rw]'*
22.61	689.15	*D*	5.01	*Ln[(D-H)/Rw]*
6.50000007	198.12	Y_0	3.35	equation (8)
0.01	0.30	Y_t	3.74	equation (9)
	600.00	*t (seconds)*	3.35	*Ln(Re/Rw)*
	0.20	*n*	1.6E-03	equation (5)





Bouwer, Herman. 1989. "The Bouwer and Rice Slug Test - An Update". Ground Water vol. 27, no. 3, May-June 1989.

Bouwer, H. and R.C. Rice. 1976. A Slug Test for Determining Hydraulic Conductivity of Unconfined Aquifers with Completely or Partially Penetrating Wells". Water Resources Research. vol 12, no. 3, June 1976.

Anal[illegible], 6/7/99

Client: **F.E. Warren**

Project:

Project No.:

Well No.: **PES-1S**

Test Date: **May 7, 1999**

Formation Tested:

Rising (R) or Falling (F) Head Test: **Falling - 2nd test**

Logger Data File:

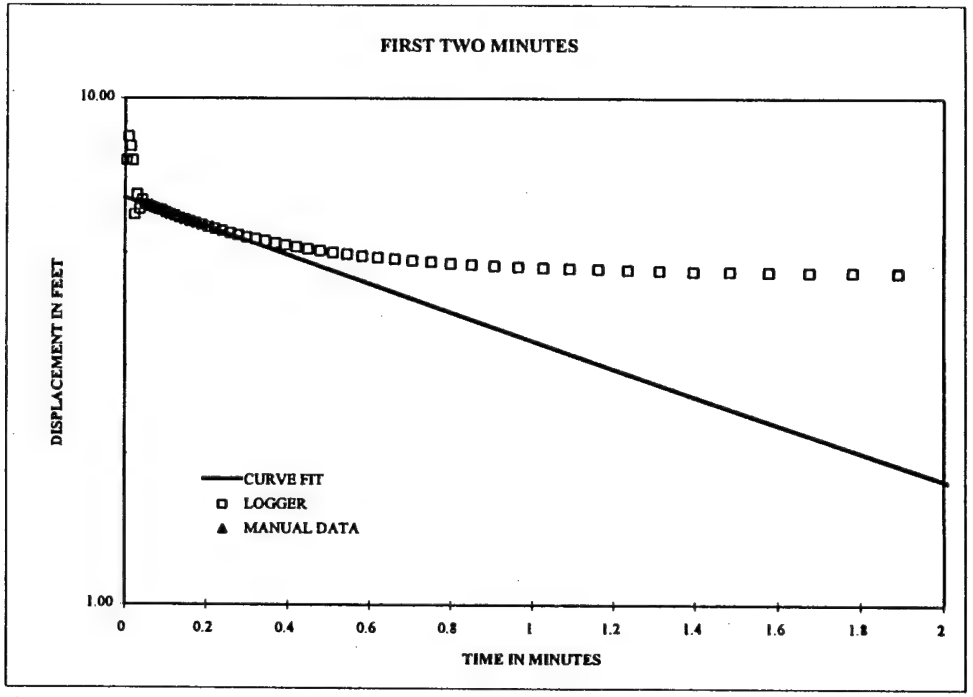
Hydraulic conductivity

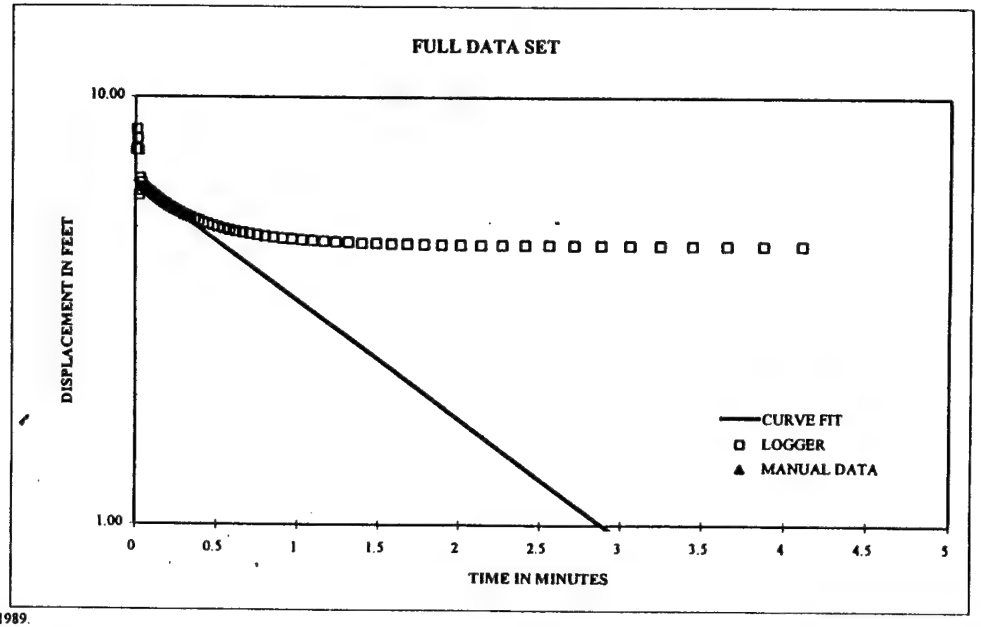
1.60E-03	cm/sec
3.15E-03	ft/min
4.53	ft/day

Casing stickup	1.49	feet
Static water level (from top of casing)	28.88	feet
Depth to bottom of screen (from ground level)	37.51	feet
Boring diameter	8.25	inches
Casing diameter	2.00	inches
Screen diameter	2.00	inches
Screen length	10.00	feet
Depth to "impermeable boundary"	50.00	feet
Porosity of filter pack	0.20	
Slug diameter (optional)		inches
Slug length (optional)		feet
Theoretical ΔH at time zero (Y_0)	0.00	feet
Actual ΔH at time zero (Y_0)	6.400	feet
ΔH at time t (Y_t)	0.010	feet
Time	10.03	min

Bouwer-Rice Parameters

feet	cm		cm	
27.39	834.85	*SW*		
10.12	308.46	*H*	120.00	*L/Rw*
27.51	838.50	*Ts*	0.45	*H/D*
0.083	2.54	*Rw*	4.60	*A*
0.171	5.21	*Rc*	0.75	*B*
0.167	5.08	*DS*	4.60	*C*
10.00	304.80	*L*	5.01	*Ln[(D-H)/Rw]'*
22.61	689.15	*D*	5.01	*Ln[(D-H)/Rw]*
6.40000006	195.07	Y_0	3.35	equation (8)
0.01	0.30	Y_t	3.74	equation (9)
	601.80	*t (seconds)*	3.35	*Ln(Re/Rw)*
	0.20	*n*	1.6E-03	equation (5)





Bouwer, Herman. 1989. "The Bouwer and Rice Slug Test - An Update". Ground Water vol. 27, no. 3, May-June 1989.

Bouwer, H. and R.C. Rice. 1976. A Slug Test for Determining Hydraulic Conductivity of Unconfined Aquifers With Completely or Partially Penetrating Wells". Water Resources Research. vol 12, no. 3, June 1976.

Client: **F.E. Warren**

Project:

Project No.:

Well No.: **PES-1S**

Test Date: **May 7, 1999**

Formation Tested:

Rising (R) or Falling (F) Head Test: **Rising - 2nd Test**

Logger Data File:

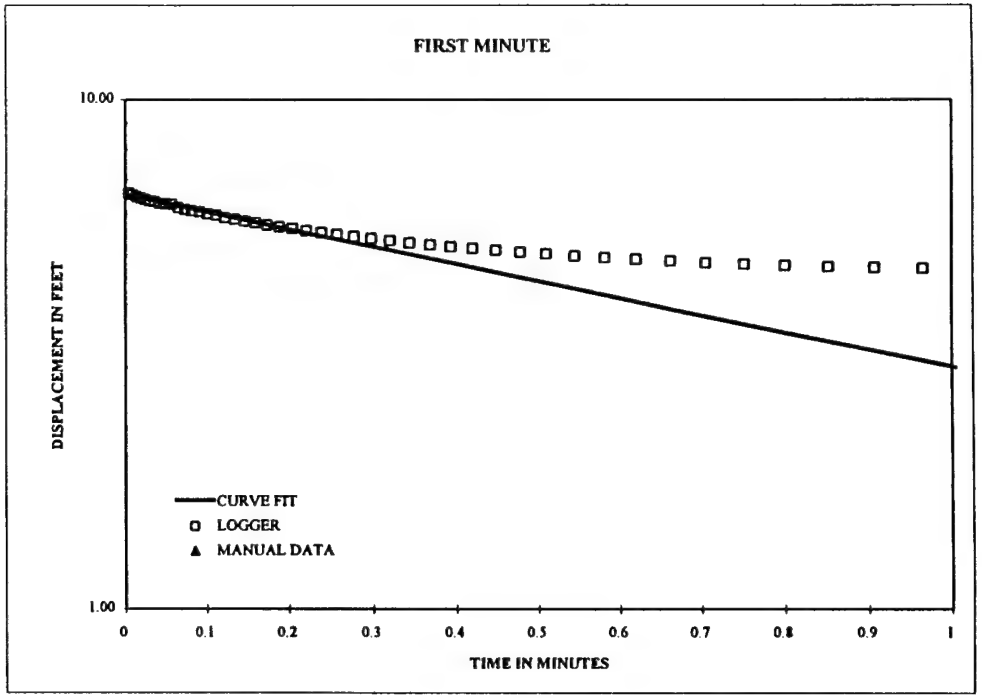
Hydraulic conductivity

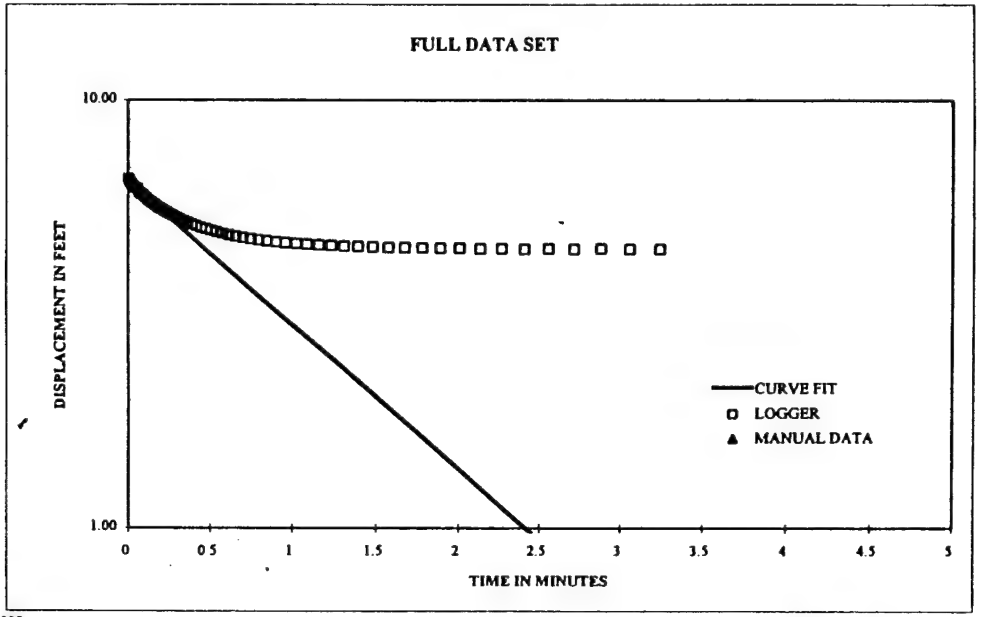
1.93E-03	cm/sec
3.80E-03	ft/min
5.47	ft/day

Casing stickup	1.49	feet
Static water level (from top of casing)	28.88	feet
Depth to bottom of screen (from ground level)	37.51	feet
Boring diameter	8.25	inches
Casing diameter	2.00	inches
Screen diameter	2.00	inches
Screen length	10.00	feet
Depth to "impermeable boundary"	50.00	feet
Porosity of filter pack	0.20	
Slug diameter (optional)		inches
Slug length (optional)		feet
Theoretical ΔH at time zero (Y_0)	0.00	feet
Actual ΔH at time zero (Y_0)	6.550	feet
ΔH at time t (Y_t)	0.010	feet
Time	8.33	min

Bouwer-Rice Parameters

feet	cm		cm	
27.39	834.85	*SW*		
10.12	308.46	*H*	120.00	*L/Rw*
27.51	838.50	*Ts*	0.45	*H/D*
0.083	2.54	*Rw*	4.60	*A*
0.171	5.21	*Rc*	0.75	*B*
0.167	5.08	*DS*	4.60	*C*
10.00	304.80	*L*	5.01	*Ln[(D-H)/Rw]'*
22.61	689.15	*D*	5.01	*Ln[(D-H)/Rw]*
6.55	199.64	Y_0	3.35	equation (8)
0.01	0.30	Y_t	3.74	equation (9)
	499.80	*t (seconds)*	3.35	*Ln(Re/Rw)*
	0.20	*n*	1.9E-03	equation (5)





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Bouwer, H. and R.C. Rice. 1976. A Slug Test for Determining Hydraulic Conductivity of Unconfined Aquifers [illegible]pletely or Partially Penetrating Wells". Water Resources Research. vol 12, no. 3, June 1976.

Anal[illegible], 6/7/99

Client: **F.E. Warren AFB**

Project:

Project No.: **722450.3005**

Well No.: **PES-2D**

Test Date: **May 7, 1999**

Formation Tested:

Rising (R) or Falling (F) Head Test: **Falling - 1st Test**

Logger Data File:

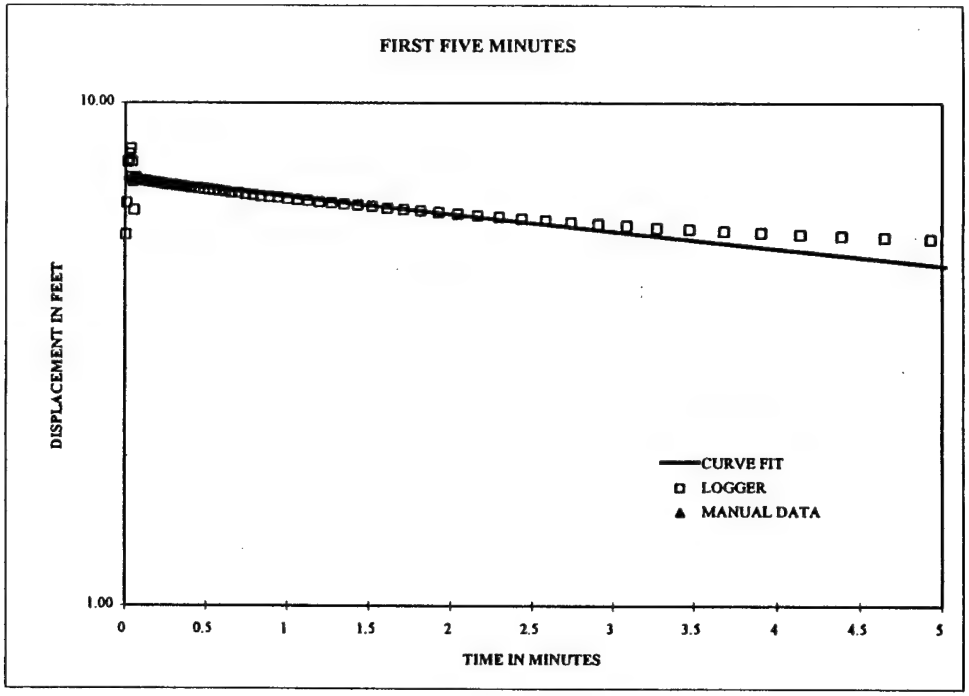
Hydraulic conductivity

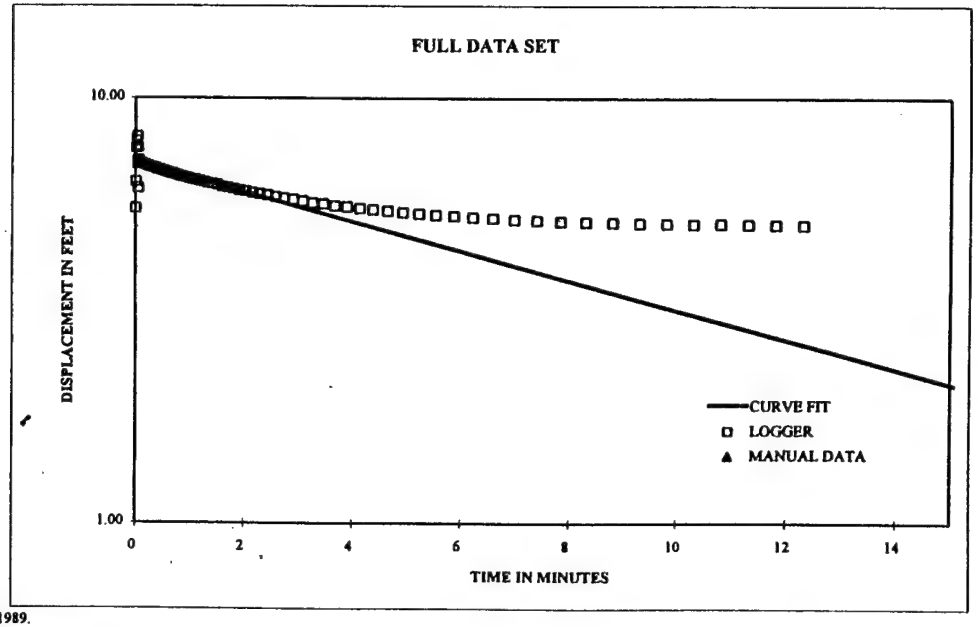
6.26E-05	cm/sec
1.23E-04	ft/min
0.18	ft/day

Casing stickup	1.63	feet
Static water level (from top of casing)	20.75	feet
Depth to bottom of screen (from ground level)	48.15	feet
Boring diameter	8.25	inches
Casing diameter	2.00	inches
Screen diameter	2.00	inches
Screen length	10.00	feet
Depth to "impermeable boundary"	50.00	feet
Porosity of filter pack	0.20	
Slug diameter (optional)		inches
Slug length (optional)		feet
Theoretical ΔH at time zero (Y_0)	0.00	feet
Actual ΔH at time zero (Y_0)	7.100	feet
ΔH at time t (Y_t)	0.150	feet
Time	48.00	min

Bouwer-Rice Parameters

feet	cm		cm	
19.12	582.78	*SW*		
29.03	884.83	*H*	120.00	*L/Rw*
38.15	1162.81	*Ts*	0.94	*H/D*
0.083	2.54	*Rw*	4.60	*A*
0.083	2.54	*Rc*	0.75	*B*
0.167	5.08	*DS*	4.60	*C*
10.00	304.80	*L*	3.10	*Ln[(D-H)/Rw]'*
30.88	941.22	*D*	3.10	*Ln[(D-H)/Rw]*
7.10000008	216.41	Y_o	4.07	equation (8)
0.15	4.57	Y_t	4.42	equation (9)
	2880.00	*t (seconds)*	4.42	*Ln(Re/Rw)*
	0.20	*n*	6.3E-05	equation (5)





Bouwer, Herman. 1989. "The Bouwer and Rice Slug Test - An Update". Ground Water vol. 27, no. 3, May-June 1989.

Bouwer, H. and R.C. Rice. 1976. A Slug Test for Determining Hydraulic Conductivity of Unconfined Aquifers With Completely or Partially Penetrating Wells". Water Resources Research. vol 12, no. 3, June 1976.

Client: **F.E. Warren AFB**

Project:

Project No.: **722450.3005**

Well No.: **PES-2D**

Test Date: **May 7, 1999**

Formation Tested:

Rising (R) or Falling (F) Head Test: **Rising - 1st Test**

Logger Data File:

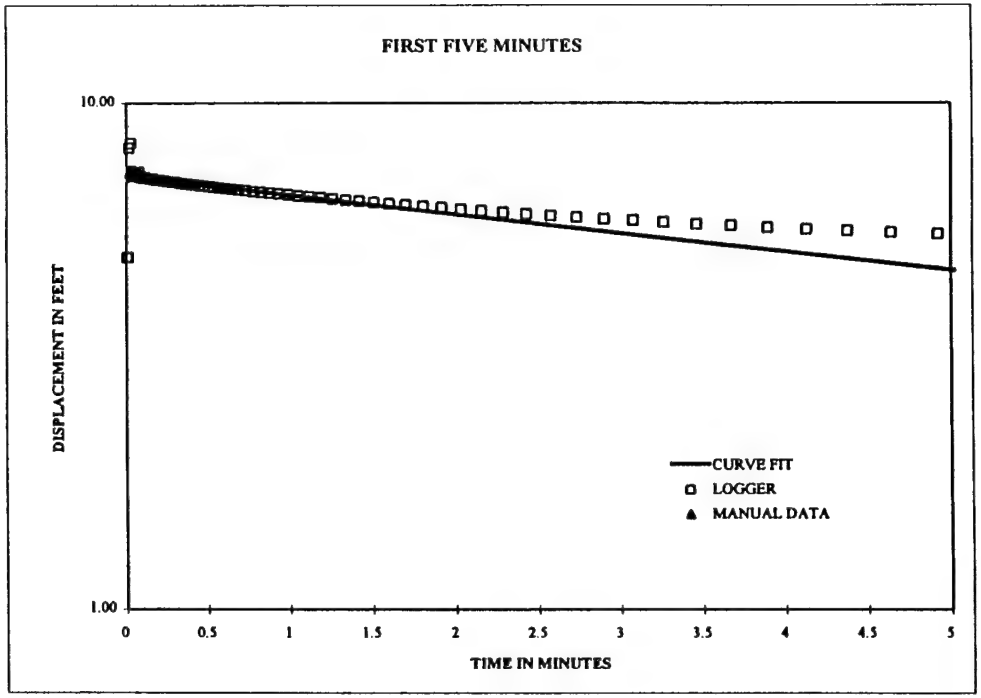
Hydraulic conductivity

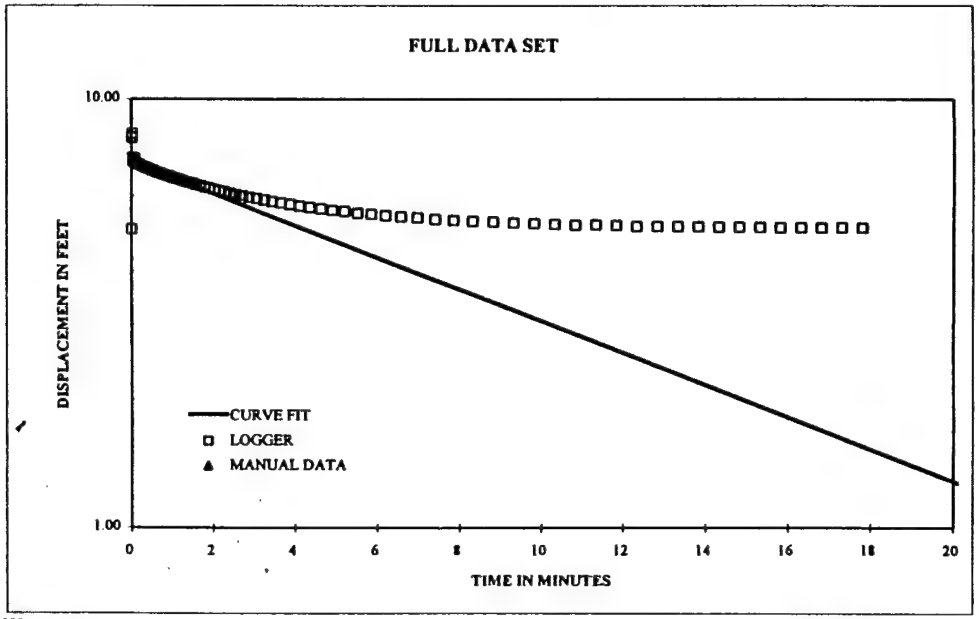
6.71E-05	cm/sec
1.32E-04	ft/min
0.19	ft/day

Casing stickup	1.63	feet
Static water level (from top of casing)	20.75	feet
Depth to bottom of screen (from ground level)	48.15	feet
Boring diameter	8.25	inches
Casing diameter	2.00	inches
Screen diameter	2.00	inches
Screen length	10.00	feet
Depth to "impermeable boundary"	50.00	feet
Porosity of filter pack	0.20	
Slug diameter (optional)		inches
Slug length (optional)		feet
Theoretical ΔH at time zero (Y_0)	0.00	feet
Actual ΔH at time zero (Y_0)	7.200	feet
ΔH at time t (Y_t)	0.150	feet
Time	45.00	min

Bouwer-Rice Parameters

feet	cm		cm	
19.12	582.78	*SW*		
29.03	884.83	*H*	120.00	*L/Rw*
38.15	1162.81	*Ts*	0.94	*H/D*
0.083	2.54	*Rw*	4.60	*A*
0.083	2.54	*Rc*	0.75	*B*
0.167	5.08	*DS*	4.60	*C*
10.00	304.80	*L*	3.10	*Ln[(D-H)/Rw]'*
30.88	941.22	*D*	3.10	*Ln[(D-H)/Rw]*
7.20000008	219.46	Y_0	4.07	equation (8)
0.15	4.57	Y_t	4.42	equation (9)
	2700.00	*t (seconds)*	4.42	*Ln(Re/Rw)*
	0.20	*n*	6.7E-05	equation (5)





Bouwer, Herman. 1989. "The Bouwer and Rice Slug Test - An Update". Ground Water vol. 27, no. 3, May-June 1989.

Bouwer, H. and R.C. Rice. 1976. A Slug Test for Determining Hydraulic Conductivity of Unconfined Aquifers [illegible]pletely or Partially Penetrating Wells". Water Resources Research. vol 12, no. 3, June 1976.

Anal[illegible], 6/7/99

Client: **F.E. Warren AFB**

Project:

Project No.: **722450.3005**

Well No.: **PES-2D**

Test Date: **May 7, 1999**

Formation Tested:

Rising (R) or Falling (F) Head Test: **Falling - 2nd Test**

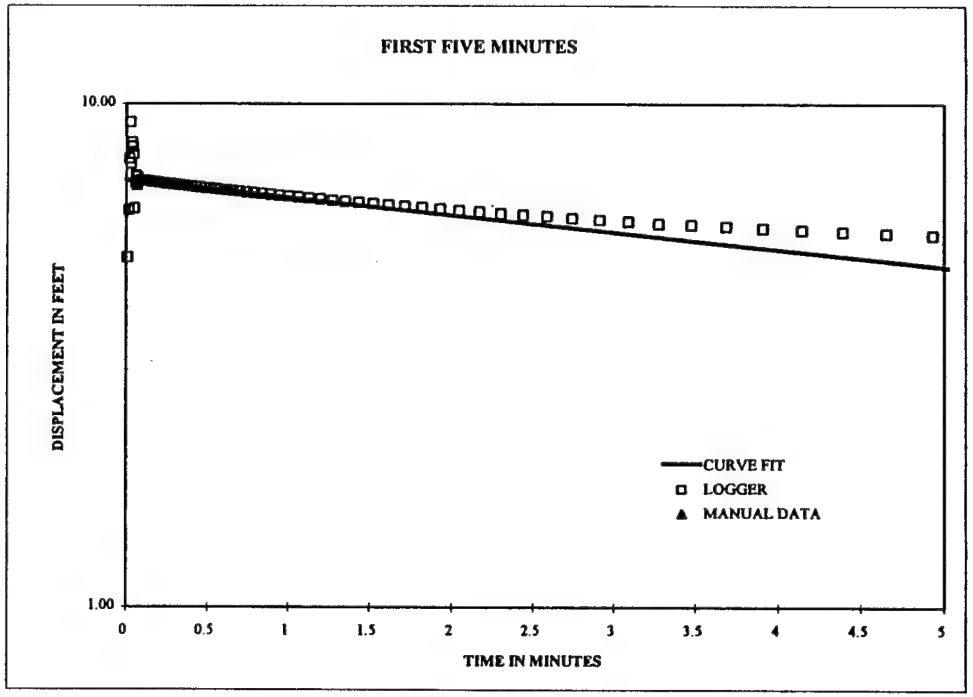
Logger Data File:

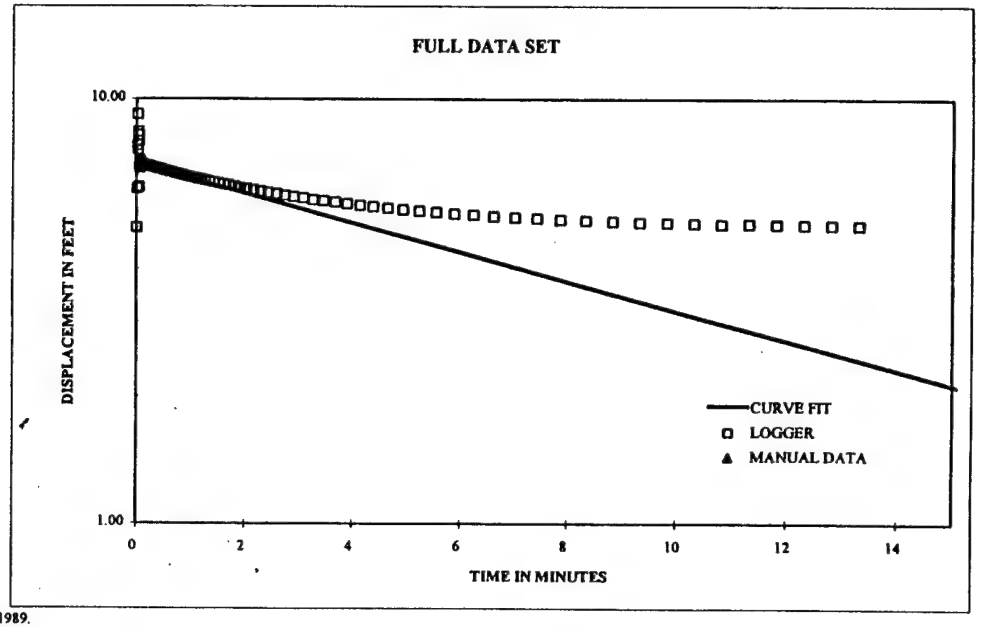
Hydraulic conductivity	6.26E-05	cm/sec
	1.23E-04	ft/min
	0.18	ft/day

Casing stickup	1.63	feet
Static water level (from top of casing)	20.75	feet
Depth to bottom of screen (from ground level)	48.15	feet
Boring diameter	8.25	inches
Casing diameter	2.00	inches
Screen diameter	2.00	inches
Screen length	10.00	feet
Depth to "impermeable boundary"	50.00	feet
Porosity of filter pack	0.20	
Slug diameter (optional)		inches
Slug length (optional)		feet
Theoretical ΔH at time zero (Y_0)	0.00	feet
Actual ΔH at time zero (Y_0)	7.100	feet
ΔH at time t (Y_t)	0.150	feet
Time	48.01	min

Bouwer-Rice Parameters

feet	cm		cm	
19.12	582.78	*SW*		
29.03	884.83	*H*	120.00	*L/Rw*
38.15	1162.81	*Ts*	0.94	*H/D*
0.083	2.54	*Rw*	4.60	*A*
0.083	2.54	*Rc*	0.75	*B*
0.167	5.08	*DS*	4.60	*C*
10.00	304.80	*L*	3.10	*Ln[(D-H)/Rw]'*
30.88	941.22	*D*	3.10	*Ln[(D-H)/Rw]*
7.10000008	216.41	Y_0	4.07	equation (8)
0.15	4.57	Y_t	4.42	equation (9)
	2880.60	*t (seconds)*	4.42	*Ln(Re/Rw)*
	0.20	*n*	6.3E-05	equation (5)





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Bouwer, H. and R.C. Rice. 1976. A Slug Test for Determining Hydraulic Conductivity of Unconfined Aquifers With Completely or Partially Penetrating Wells". Water Resources Research. vol 12, no. 3, June 1976.

Client: **F.E. Warren AFB**

Project:

Project No.: **722450.3005**

Well No.: **PES-2D**

Test Date: **May 7, 1999**

Formation Tested:

Rising (R) or Falling (F) Head Test: **Rising - 2st Test**

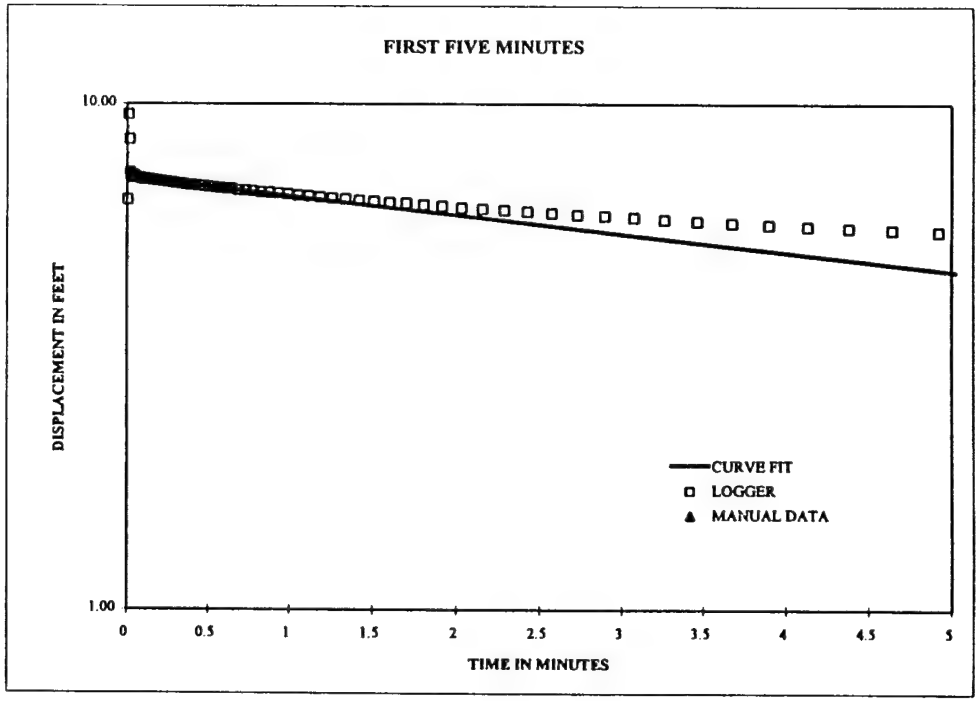
Logger Data File:

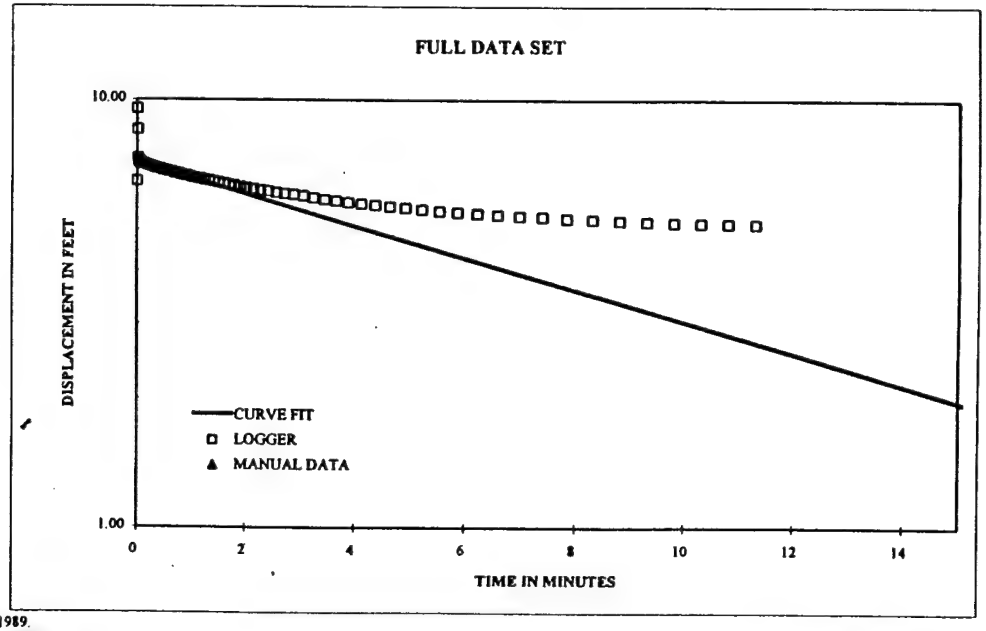
Hydraulic conductivity	6.73E-05	cm/sec
	1.33E-04	ft/min
	0.19	ft/day

Casing stickup	1.63	feet
Static water level (from top of casing)	20.75	feet
Depth to bottom of screen (from ground level)	48.15	feet
Boring diameter	8.25	inches
Casing diameter	2.00	inches
Screen diameter	2.00	inches
Screen length	10.00	feet
Depth to "impermeable boundary"	50.00	feet
Porosity of filter pack	0.20	
Slug diameter (optional)		inches
Slug length (optional)		feet
Theoretical ΔH at time zero (Y_0)	0.00	feet
Actual ΔH at time zero (Y_0)	7.200	feet
ΔH at time t (Y_t)	0.150	feet
Time	44.83	min

Bouwer-Rice Parameters

feet	cm		cm	
19.12	582.78	*SW*		
29.03	884.83	*H*	120.00	*L/Rw*
38.15	1162.81	*Ts*	0.94	*H/D*
0.083	2.54	*Rw*	4.60	*A*
0.083	2.54	*Rc*	0.75	*B*
0.167	5.08	*DS*	4.60	*C*
10.00	304.80	*L*	3.10	*Ln[(D-H)/Rw]'*
30.88	941.22	*D*	3.10	*Ln[(D-H)/Rw]*
7.20000008	219.46	Y_e	4.07	equation (8)
0.15	4.57	Y_t	4.42	equation (9)
	2689.80	*t (seconds)*	4.42	*Ln(Re/Rw)*
	0.20	*n*	6.7E-05	equation (5)





Bouwer, Herman. 1989. "The Bouwer and Rice Slug Test - An Update". Ground Water vol. 27, no. 3, May-June 1989.

Bouwer, H. and R.C. Rice. 1976. A Slug Test for Determining Hydraulic Conductivity of Unconfined Aquifers W[illegible]pletely or Partially Penetrating Wells". Water Resources Research. vol 12, no. 3, June 1976.

Anal[illegible] 6/7/99

Client: **F.E. Warren**

Project: **Landfill 3**

Project No.: **722450.3005**

Well No.: **PES-3D**

Test Date: **May 10, 1999**

Formation Tested:

Rising (R) or Falling (F) Head Test: **Rising**

Logger Data File:

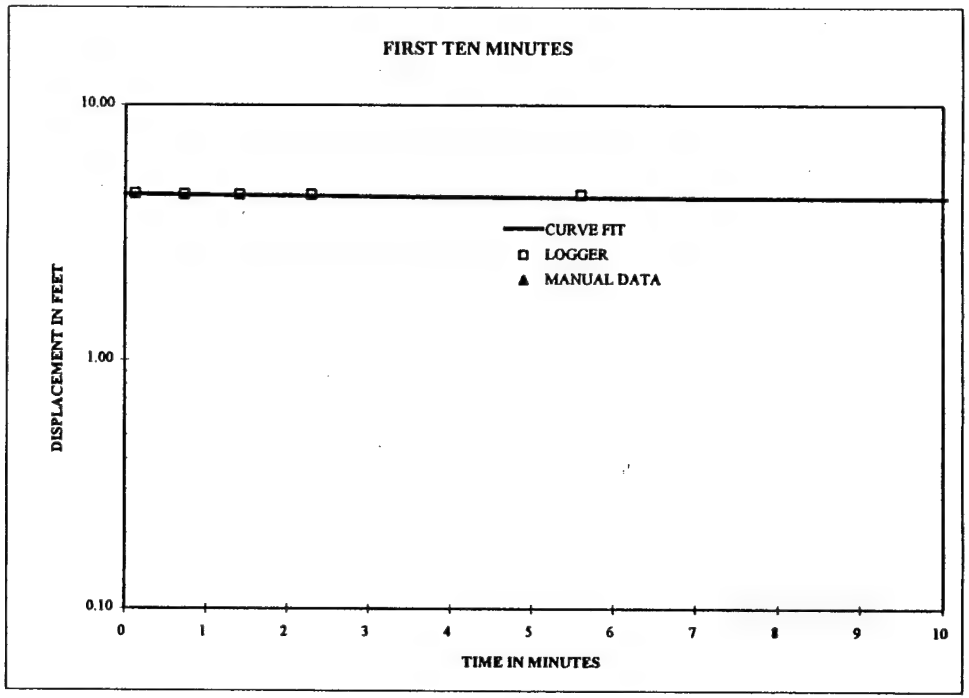
Hydraulic conductivity

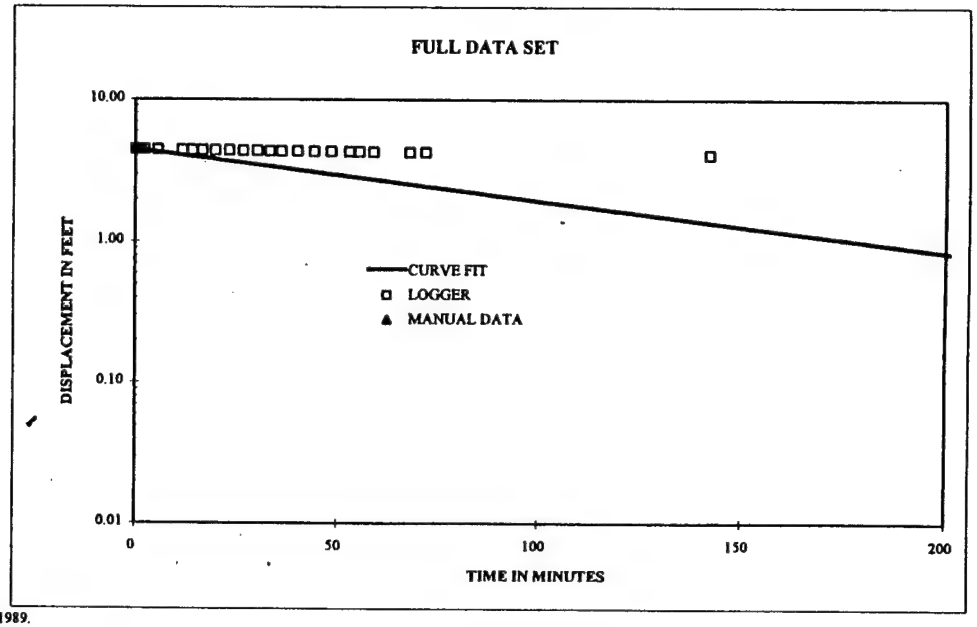
1.04E-05	cm/sec
2.05E-05	ft/min
0.03	ft/day

Casing stickup	2.05	feet
Static water level (from top of casing)	9.34	feet
Depth to bottom of screen (from ground level)	36.95	feet
Boring diameter	8.00	inches
Casing diameter	2.00	inches
Screen diameter	2.00	inches
Screen length	5.00	feet
Depth to "impermeable boundary"	50.00	feet
Porosity of filter pack	0.20	
Slug diameter (optional)		inches
Slug length (optional)		feet
Theoretical ΔH at time zero (Y_0)	0.00	feet
Actual ΔH at time zero (Y_0)	4.500	feet
ΔH at time t (Y_t)	2.500	feet
Time	70.00	min

Bouwer-Rice Parameters

feet	cm		cm	
7.29	222.20	*SW*		
29.66	904.04	*H*	60.00	*L/Rw*
31.95	973.84	*Ts*	0.69	*H/D*
0.083	2.54	*Rw*	3.30	*A*
0.083	2.54	*Rc*	0.50	*B*
0.167	5.08	*DS*	2.90	*C*
5.00	152.40	*L*	5.05	*Ln[(D-H)/Rw]'*
42.71	1301.80	*D*	5.05	*Ln[(D-H)/Rw]*
4.5	137.16	Y_0	3.52	equation (8)
2.5	76.20	Y_t	4.24	equation (9)
	4200.00	*t (seconds)*	3.52	*Ln(Re/Rw)*
	0.20	*n*	1.0E-05	equation (5)





Bouwer, Herman. 1989. "The Bouwer and Rice Slug Test - An Update". Ground Water vol. 27, no. 3, May-June 1989.

Bouwer, H. and R.C. Rice. 1976. A Slug Test for Determining Hydraulic Conductivity of Unconfined Aquifers With Completely or Partially Penetrating Wells". Water Resources Research. vol 12, no. 3, June 1976.

Client: **F.E. Warren AFB**

Project: **Landfill 3**

Project No.: **722450.3005**

Well No.: **PES-4D**

Test Date: **May 7, 1999**

Formation Tested:

Rising (R) or Falling (F) Head Test: **Falling - 1st Test**

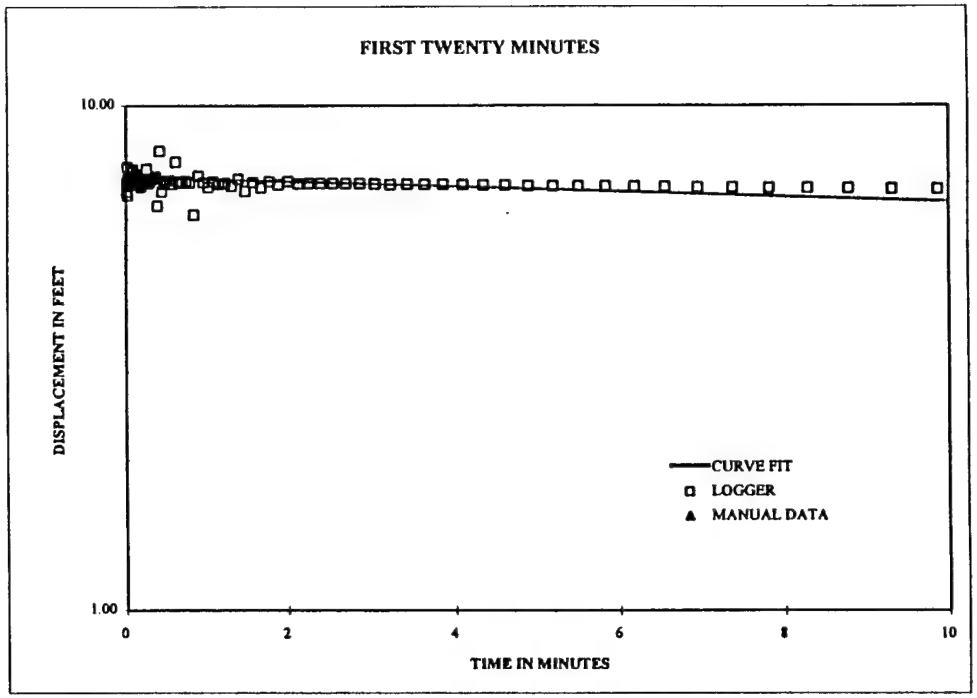
Logger Data File:

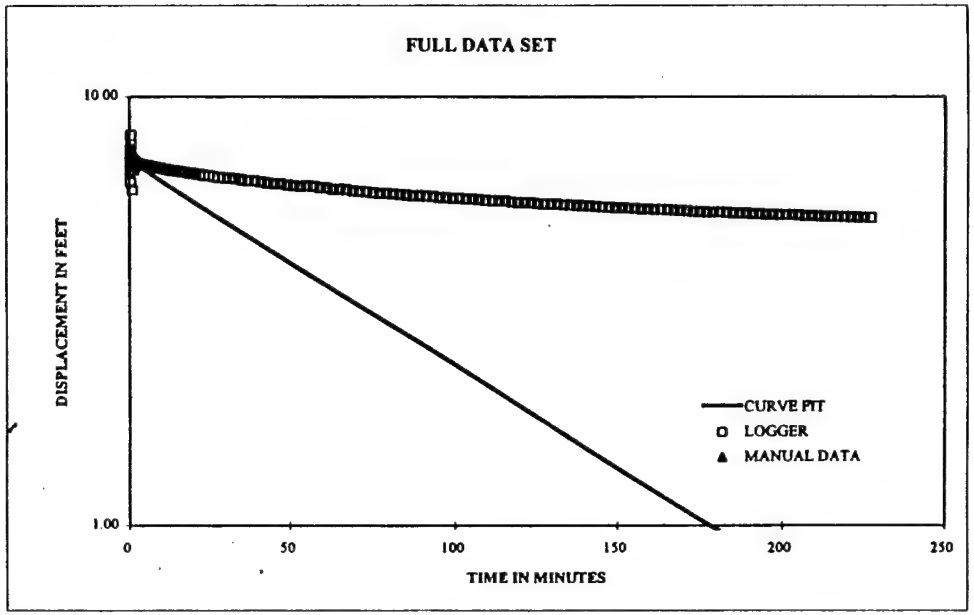
Hydraulic conductivity	1.66E-05	cm/sec
	3.27E-05	ft/min
	0.05	ft/day

Casing stickup	1.83	feet
Static water level (from top of casing)	18.58	feet
Depth to bottom of screen (from ground level)	47.67	feet
Boring diameter	8.25	inches
Casing diameter	2.00	inches
Screen diameter	2.00	inches
Screen length	5.00	feet
Depth to "impermeable boundary"	50.00	feet
Porosity of filter pack	0.20	
Slug diameter (optional)		inches
Slug length (optional)		feet
Theoretical ΔH at time zero (Y_0)	0.00	feet
Actual ΔH at time zero (Y_0)	7.150	feet
ΔH at time t (Y_t)	0.150	feet
Time	350.00	min

Bouwer-Rice Parameters

feet	cm		cm	
16.75	510.54	*SW*		
30.92	942.44	*H*	60.00	*L/Rw*
42.67	1300.58	*Ts*	0.93	*H/D*
0.083	2.54	*Rw*	3.30	*A*
0.083	2.54	*Rc*	0.50	*B*
0.167	5.08	*DS*	2.90	*C*
5.00	152.40	*L*	3.33	*Ln[(D-H)/Rw]'*
33.25	1013.46	*D*	3.33	*Ln[(D-H)/Rw]*
7.15000001	217.93	Y_0	3.72	equation (8)
0.15	4.57	Y_t	4.27	equation (9)
	21000.00	*t (seconds)*	4.27	*Ln(Re/Rw)*
	0.20	*n*	1.7E-05	equation (5)





Bouwer, Herman. 1989. "The Bouwer and Rice Slug Test - An Update". Ground Water vol. 27, no. 3, May-June 1989.

Bouwer, H. and R.C. Rice. 1976. A Slug Test for Determining Hydraulic Conductivity of Unconfined Aquifers [illegible]mpletely or Partially Penetrating Wells". Water Resources Research. vol 12, no. 3, June 1976.

Anal[illegible], 6/7/99

Client: **F.E. Warren AFB**

Project: **Landfill 3**

Project No.: **722450.3005**

Well No.: **PES-4D**

Test Date: **May 7, 1999**

Formation Tested:

Rising (R) or Falling (F) Head Test: **Falling - 2nd Test**

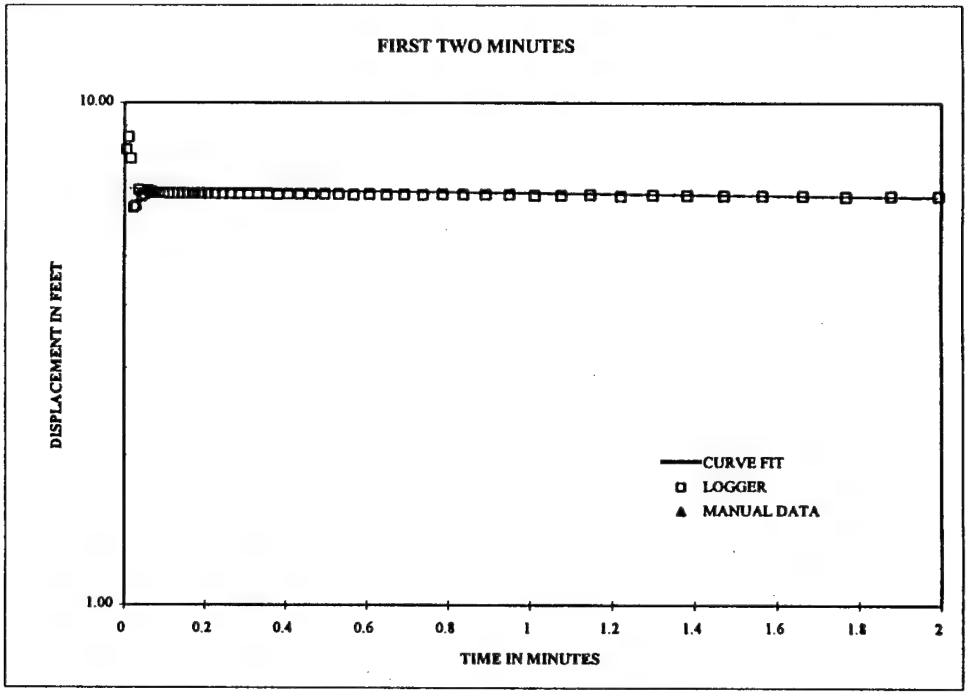
Logger Data File:

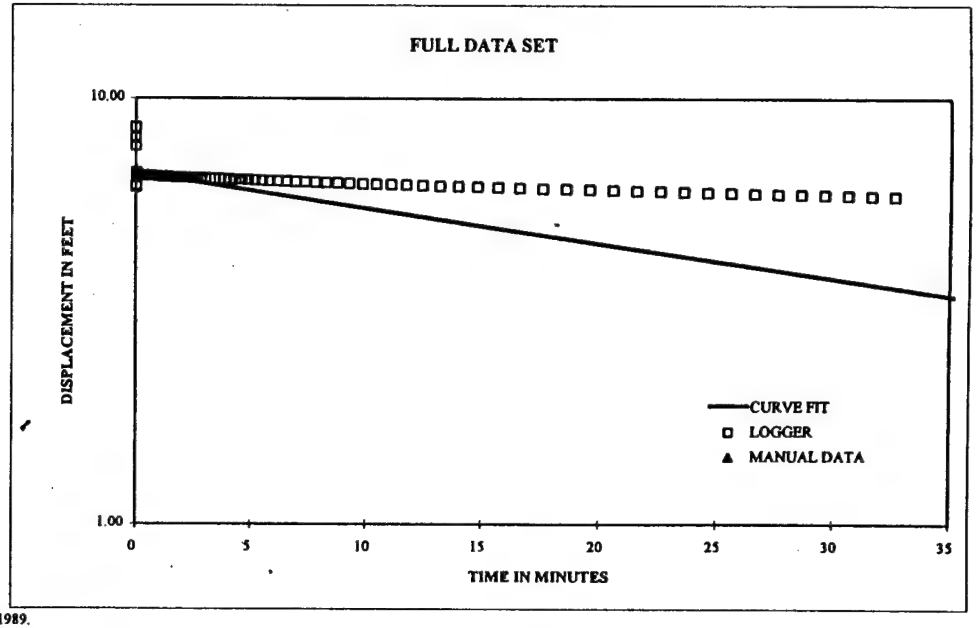
Hydraulic conductivity **2.86E-05 cm/sec**
5.63E-05 ft/min
0.08 ft/day

Casing stickup	1.83	feet
Static water level (from top of casing)	18.58	feet
Depth to bottom of screen (from ground level)	47.67	feet
Boring diameter	8.25	inches
Casing diameter	2.00	inches
Screen diameter	2.00	inches
Screen length	5.00	feet
Depth to "impermeable boundary"	50.00	feet
Porosity of filter pack	0.20	
Slug diameter (optional)		inches
Slug length (optional)		feet
Theoretical ΔH at time zero (Y_0)	0.00	feet
Actual ΔH at time zero (Y_0)	6.700	feet
ΔH at time t (Y_t)	0.150	feet
Time	200.00	min

Bouwer-Rice Parameters

feet	cm		cm	
16.75	510.54	*SW*		
30.92	942.44	*H*	60.00	*L/Rw*
42.67	1300.58	*Ts*	0.93	*H/D*
0.083	2.54	*Rw*	3.30	*A*
0.083	2.54	*Rc*	0.50	*B*
0.167	5.08	*DS*	2.90	*C*
5.00	152.40	*L*	3.33	*Ln[(D-H)/Rw]*
33.25	1013.46	*D*	3.33	*Ln[(D-H)/Rw]*
6.70000007	204.22	Y_0	3.72	equation (8)
0.15	4.57	Y_t	4.27	equation (9)
	12000.00	*t (seconds)*	4.27	*Ln(Re/Rw)*
	0.20	*n*	2.9E-05	equation (5)





Bouwer, Herman. 1989. "The Bouwer and Rice Slug Test - An Update". Ground Water vol. 27, no. 3, May-June 1989.

Bouwer, H. and R.C. Rice. 1976. A Slug Test for Determining Hydraulic Conductivity of Unconfined Aquifers With Completely or Partially Penetrating Wells". Water Resources Research. vol 12, no. 3, June 1976.

Client: **F.E. Warren**

Project: **Landfill 3**

Project No.: **722450.3005**

Well No.: **PES-4D**

Test Date: **May 7, 1999**

Formation Tested:

Rising (R) or Falling (F) Head Test: **Rising - 2nd Test**

Logger Data File:

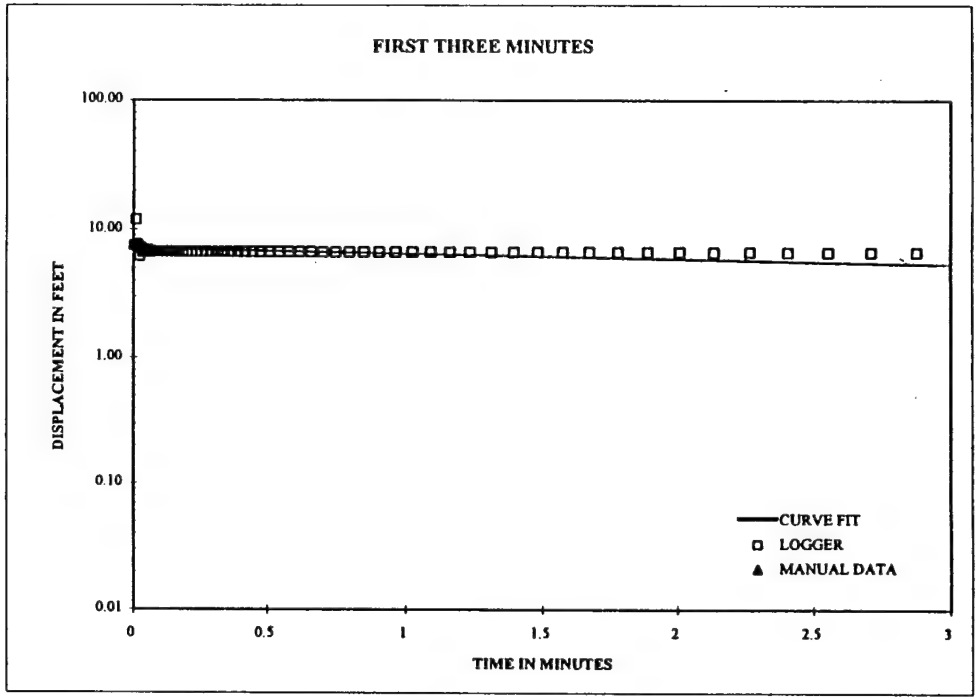
Hydraulic conductivity

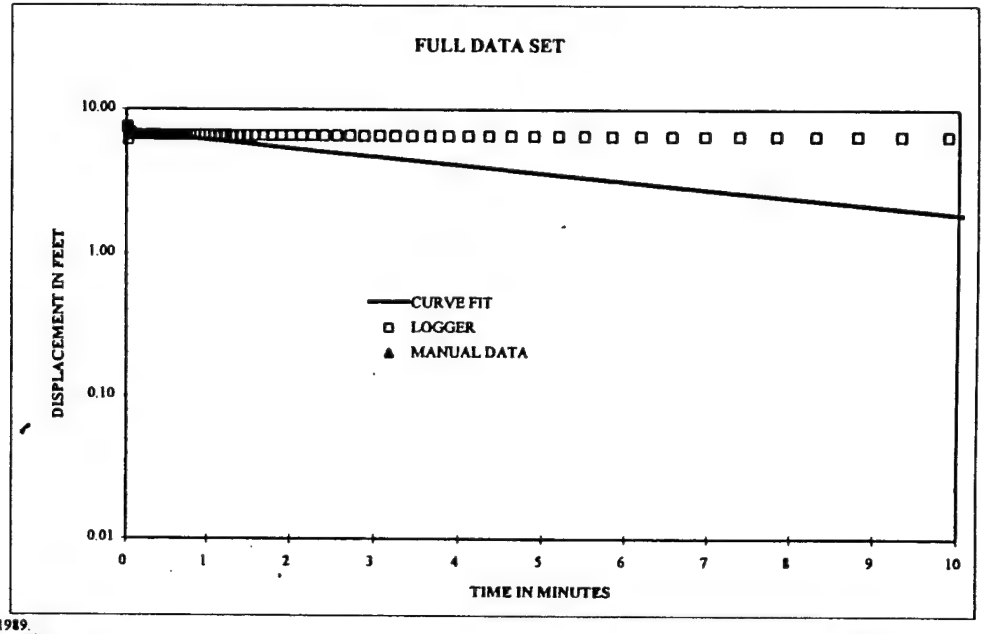
2.00E-04	cm/sec
3.93E-04	ft/min
0.57	ft/day

Casing stickup	1.83	feet
Static water level (from top of casing)	18.58	feet
Depth to bottom of screen (from ground level)	47.67	feet
Boring diameter	8.25	inches
Casing diameter	2.00	inches
Screen diameter	2.00	inches
Screen length	5.00	feet
Depth to "impermeable boundary"	50.00	feet
Porosity of filter pack	0.20	
Slug diameter (optional)		inches
Slug length (optional)		feet
Theoretical ΔH at time zero (Y_0)	0.00	feet
Actual ΔH at time zero (Y_0)	7.100	feet
ΔH at time t (Y_t)	0.010	feet
Time	49.50	min

Bouwer-Rice Parameters

feet	cm		cm	
16.75	510.54	*SW*		
30.92	942.44	*H*	60.00	*L/Rw*
42.67	1300.58	*Ts*	0.93	*H/D*
0.083	2.54	*Rw*	3.30	*A*
0.083	2.54	*Rc*	0.50	*B*
0.167	5.08	*DS*	2.90	*C*
5.00	152.40	*L*	3.33	*Ln[(D-H)/Rw]'*
33.25	1013.46	*D*	3.33	*Ln[(D-H)/Rw]*
7.1	216.41	Y_e	3.72	equation (8)
0.01	0.30	Y_t	4.27	equation (9)
	2970.00	*t (seconds)*	4.27	*Ln(Re/Rw)*
	0.20	*n*	2.0E-04	equation (5)





Bouwer, Herman. 1989. "The Bouwer and Rice Slug Test - An Update". Ground Water vol. 27, no. 3, May-June 1989.

Bouwer, H. and R.C. Rice. 1976. A Slug Test for Determining Hydraulic Conductivity of Unconfined Aquifers W[illegible]letely or Partially Penetrating Wells". Water Resources Research. vol 12, no. 3, June 1976.

AnalST[illegible] 6/7/99

Client: **F.E. Warren**

Project: **Landfill 3**

Project No.: **722450.3005**

Well No.: **PES-5D**

Test Date: **May 10, 1999**

Formation Tested:

Rising (R) or Falling (F) Head Test: **Rising**

Logger Data File:

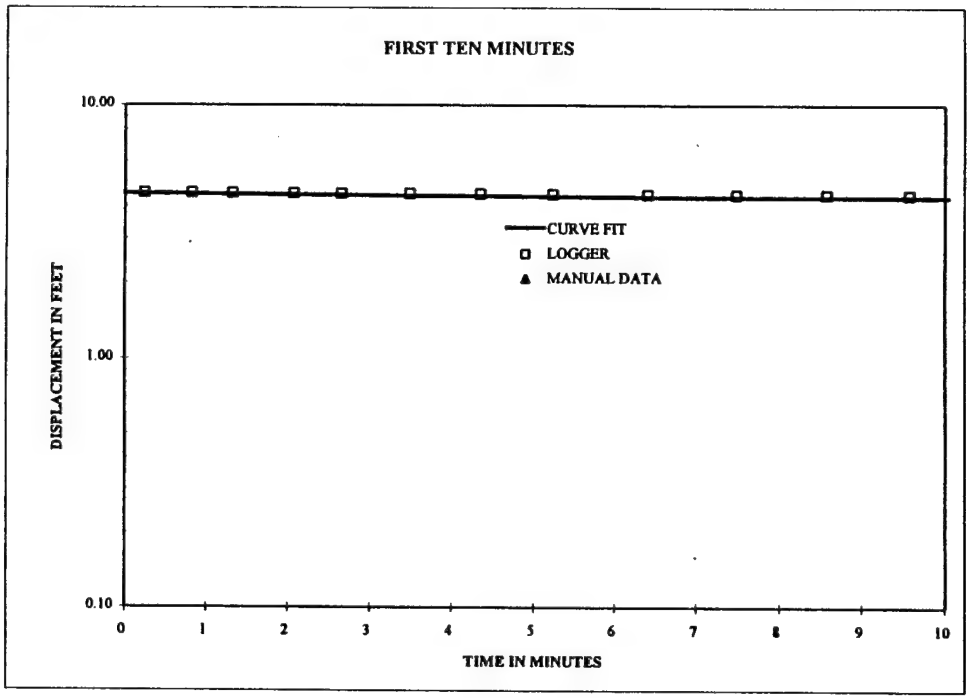
Hydraulic conductivity

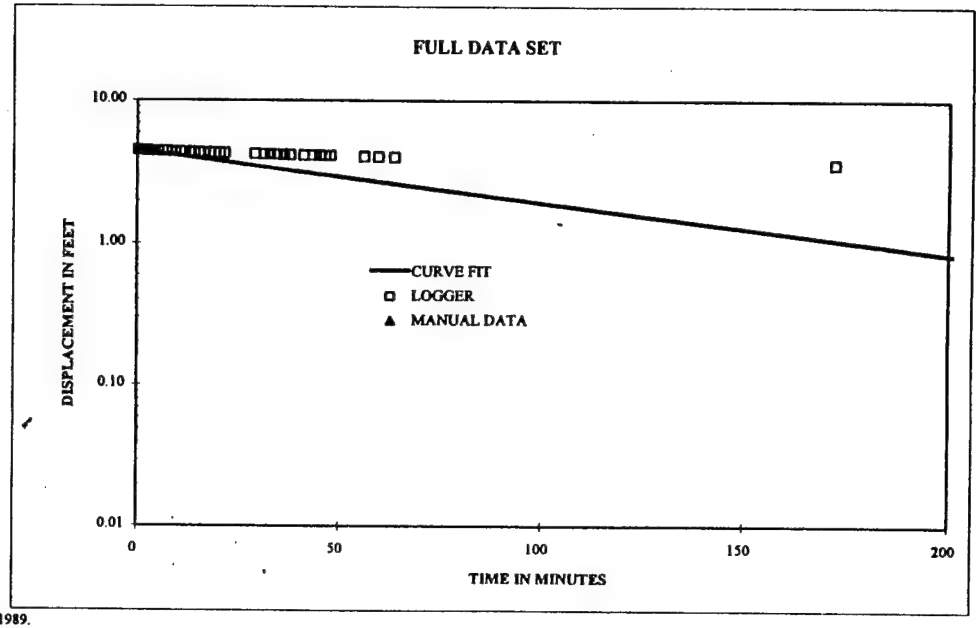
1.05E-05	cm/sec
2.07E-05	ft/min
0.03	ft/day

Casing stickup	1.69	feet
Static water level (from top of casing)	7.20	feet
Depth to bottom of screen (from ground level)	37.81	feet
Boring diameter	8.00	inches
Casing diameter	2.00	inches
Screen diameter	2.00	inches
Screen length	5.00	feet
Depth to "impermeable boundary"	50.00	feet
Porosity of filter pack	0.20	
Slug diameter (optional)		inches
Slug length (optional)		feet
Theoretical ΔH at time zero (Y_0)	0.00	feet
Actual ΔH at time zero (Y_0)	4.500	feet
ΔH at time t (Y_t)	2.500	feet
Time	70.00	min

Bouwer-Rice Parameters

feet	cm		cm	
5.51	167.94	*SW*		
32.3	984.50	*H*	60.00	*L/Rw*
32.81	1000.05	*Ts*	0.73	*H/D*
0.083	2.54	*Rw*	3.30	*A*
0.083	2.54	*Rc*	0.50	*B*
0.167	5.08	*DS*	2.90	*C*
5.00	152.40	*L*	4.99	*Ln[(D-H)/Rw]'*
44.49	1356.06	*D*	4.99	*Ln[(D-H)/Rw]*
4.5	137.16	Y_o	3.56	equation (8)
2.5	76.20	Y_t	4.29	equation (9)
	4200.00	*t (seconds)*	3.56	*Ln(Re/Rw)*
	0.20	*n*	1.1E-05	equation (5)





Bouwer, Herman. 1989. "The Bouwer and Rice Slug Test - An Update". Ground Water vol. 27, no. 3, May-June 1989.

Bouwer, H. and R.C. Rice. 1976. A Slug Test for Determining Hydraulic Conductivity of Unconfined Aquifers With Completely or Partially Penetrating Wells". Water Resources Research. vol 12, no. 3, June 1976.

Client: **F.E. Warren**

Project: **Landfill 3**

Project No.: **722450.3005**

Well No.: **PES-6S**

Test Date: **May 7, 1999**

Formation Tested:

Rising (R) or Falling (F) Head Test: **Falling-1st Test**

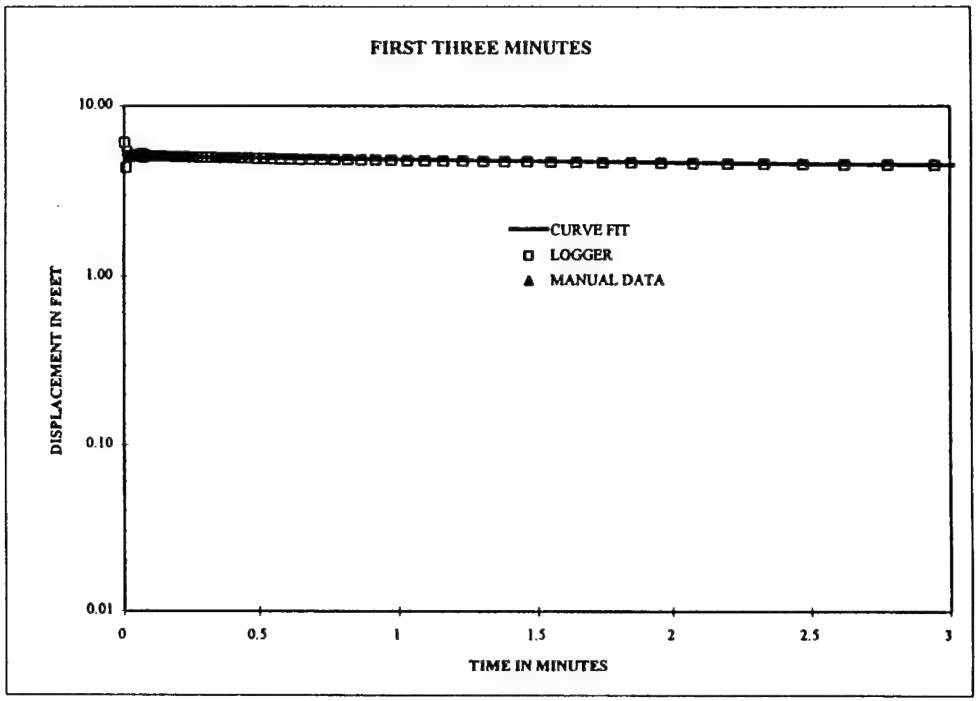
Logger Data File:

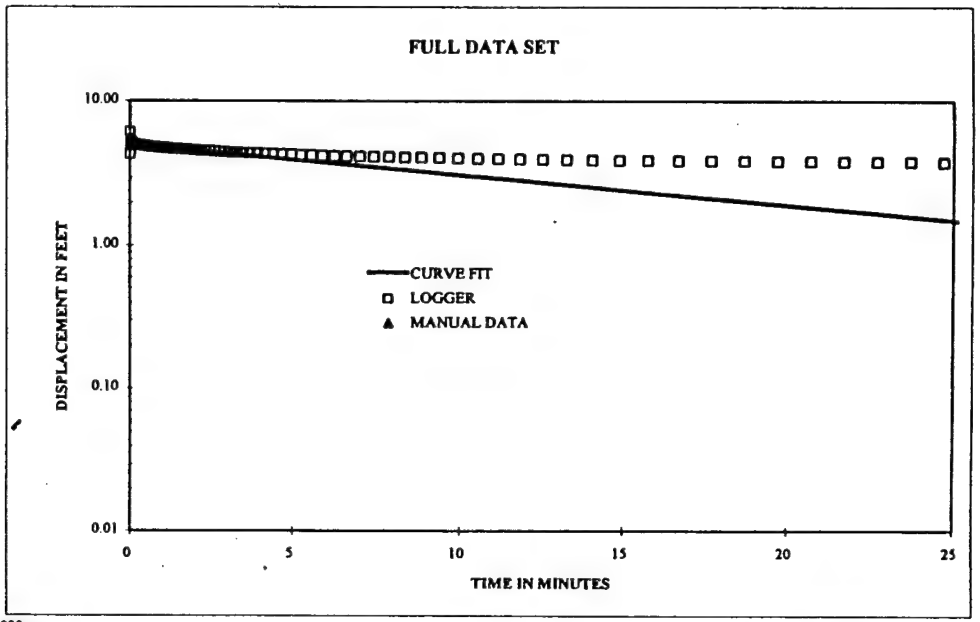
Hydraulic conductivity **3.15E-05** cm/sec
6.20E-05 ft/min
0.09 ft/day

Casing stickup	1.60	feet
Static water level (from top of casing)	12.42	feet
Depth to bottom of screen (from ground level)	30.40	feet
Boring diameter	8.25	inches
Casing diameter	2.00	inches
Screen diameter	2.00	inches
Screen length	10.00	feet
Depth to "impermeable boundary"	50.00	feet
Porosity of filter pack	0.20	
Slug diameter (optional)		inches
Slug length (optional)		feet
Theoretical ΔH at time zero (Y_0)	0.00	feet
Actual ΔH at time zero (Y_0)	5.100	feet
ΔH at time t (Y_t)	1.500	feet
Time	25.00	min

Bouwer-Rice Parameters

feet	cm		cm	
10.82	329.79	*SW*		
19.58	596.80	*H*	120.00	*L/Rw*
20.4	621.79	*Ts*	0.50	*H/D*
0.083	2.54	*Rw*	4.60	*A*
0.083	2.54	*Rc*	0.75	*B*
0.167	5.08	*DS*	4.60	*C*
10.00	304.80	*L*	5.46	*Ln[(D-H)/Rw]'*
39.18	1194.21	*D*	5.46	*Ln[(D-H)/Rw]*
5.10000005	155.45	Y_0	3.65	equation (8)
1.5	45.72	Y_t	4.17	equation (9)
	1500.00	*t (seconds)*	3.65	*Ln(Re/Rw)*
	0.20	*n*	3.2E-05	equation (5)





Bouwer, Herman. 1989. "The Bouwer and Rice Slug Test - An Update". Ground Water vol. 27, no. 3, May-June 1989.

Bouwer, H. and R.C. Rice. 1976. A Slug Test for Determining Hydraulic Conductivity of Unconfined Aquifers [illegible]ely or Partially Penetrating Wells". Water Resources Research. vol 12, no. 3, June 1976.

Anal[illegible], 6/8/99

Client: **F.E. Warren**

Project: **Landfill 3**

Project No.: **722450.3005**

Well No.: **PES-6S**

Test Date: **May 7, 1999**

Formation Tested:

Rising (R) or Falling (F) Head Test: **Rising-2nd Test**

Logger Data File:

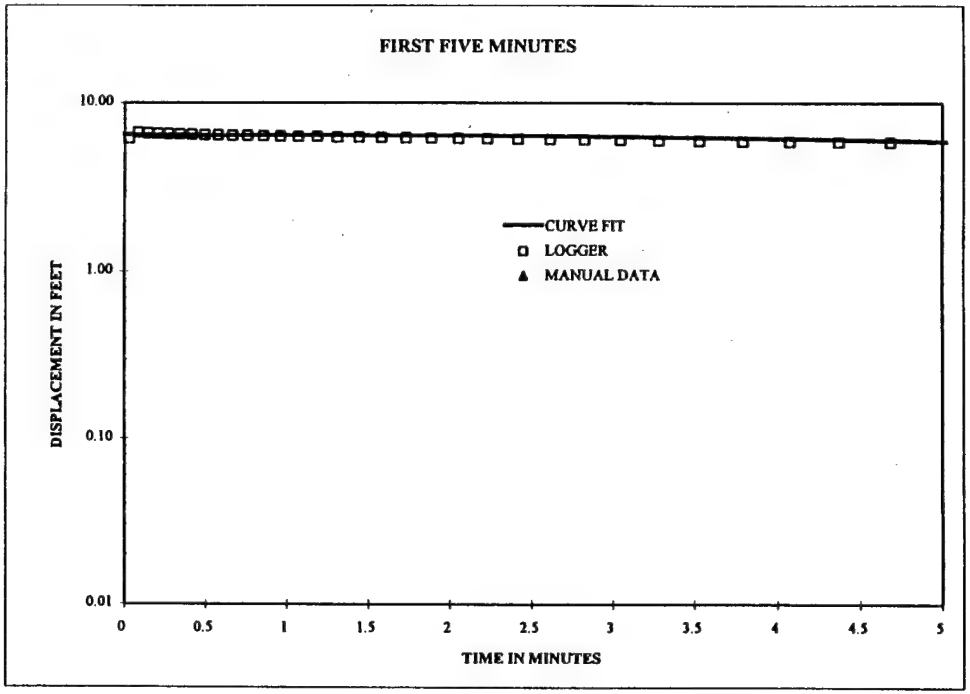
Hydraulic conductivity

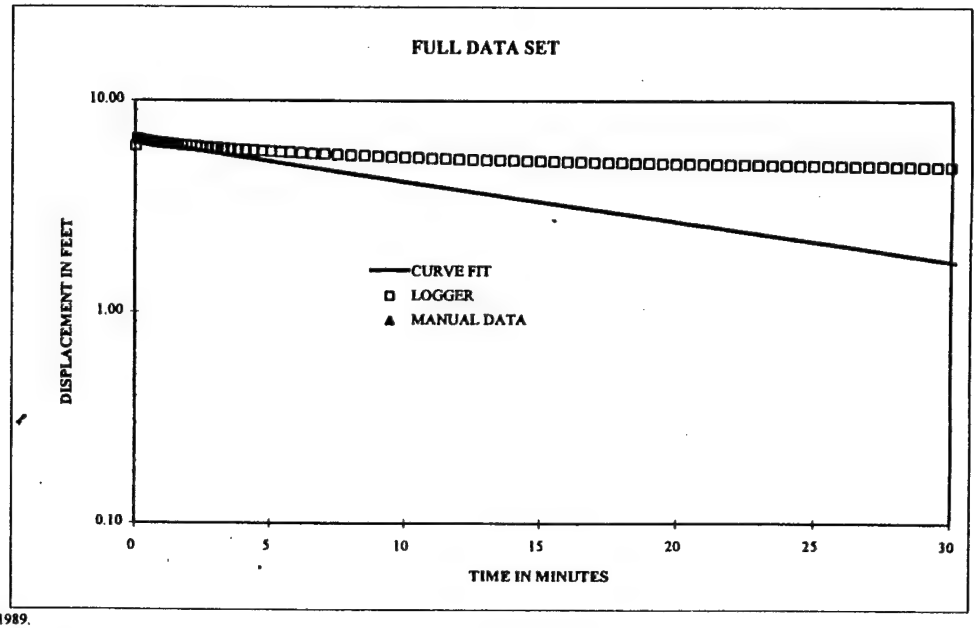
2.82E-05	cm/sec
5.55E-05	ft/min
0.08	ft/day

Casing stickup	1.60	feet
Static water level (from top of casing)	12.42	feet
Depth to bottom of screen (from ground level)	30.40	feet
Boring diameter	8.00	inches
Casing diameter	2.00	inches
Screen diameter	2.00	inches
Screen length	10.00	feet
Depth to "impermeable boundary"	50.00	feet
Porosity of filter pack	0.20	
Slug diameter (optional)		inches
Slug length (optional)		feet
Theoretical ΔH at time zero (Y_0)	0.00	feet
Actual ΔH at time zero (Y_0)	6.500	feet
ΔH at time t (Y_t)	4.500	feet
Time	8.40	min

Bouwer-Rice Parameters

feet	cm		cm	
10.82	329.79	*SW*		
19.58	596.80	*H*	120.00	*L/Rw*
20.4	621.79	*Ts*	0.50	*H/D*
0.083	2.54	*Rw*	4.60	*A*
0.083	2.54	*Rc*	0.75	*B*
0.167	5.08	*DS*	4.60	*C*
10.00	304.80	*L*	5.46	*Ln[(D-H)/Rw]'*
39.18	1194.21	*D*	5.46	*Ln[(D-H)/Rw]*
6.50000007	198.12	Y_0	3.65	equation (8)
4.5	137.16	Y_t	4.17	equation (9)
	504.00	*t (seconds)*	3.65	*Ln(Re/Rw)*
	0.20	*n*	2.8E-05	equation (6)





Bouwer, Herman. 1989. "The Bouwer and Rice Slug Test - An Update". Ground Water vol. 27, no. 3, May-June 1989.

Bouwer, H. and R.C. Rice. 1976. A Slug Test for Determining Hydraulic Conductivity of Unconfined Aquifers With Completely or Partially Penetrating Wells". Water Resources Research. vol 12, no. 3, June 1976.

Client: **F.E. Warren**

Project: **Landfill 3**

Project No.: **722450.3005**

Well No.: **PES-6S**

Test Date: **May 7, 1999**

Formation Tested:

Rising (R) or Falling (F) Head Test: **Falling-2nd Test**

Logger Data File:

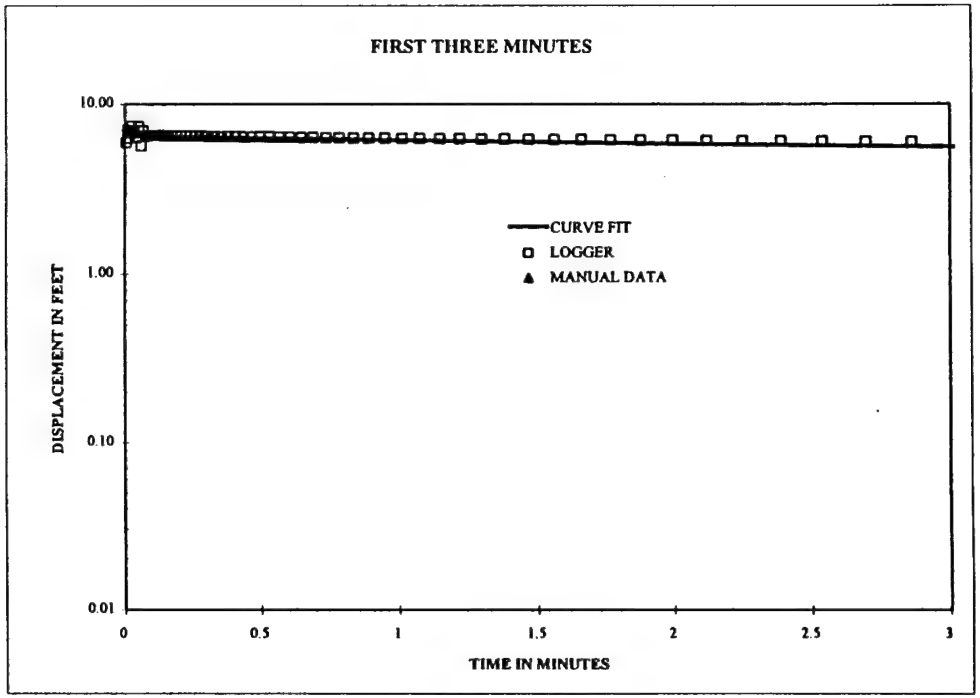
Hydraulic conductivity

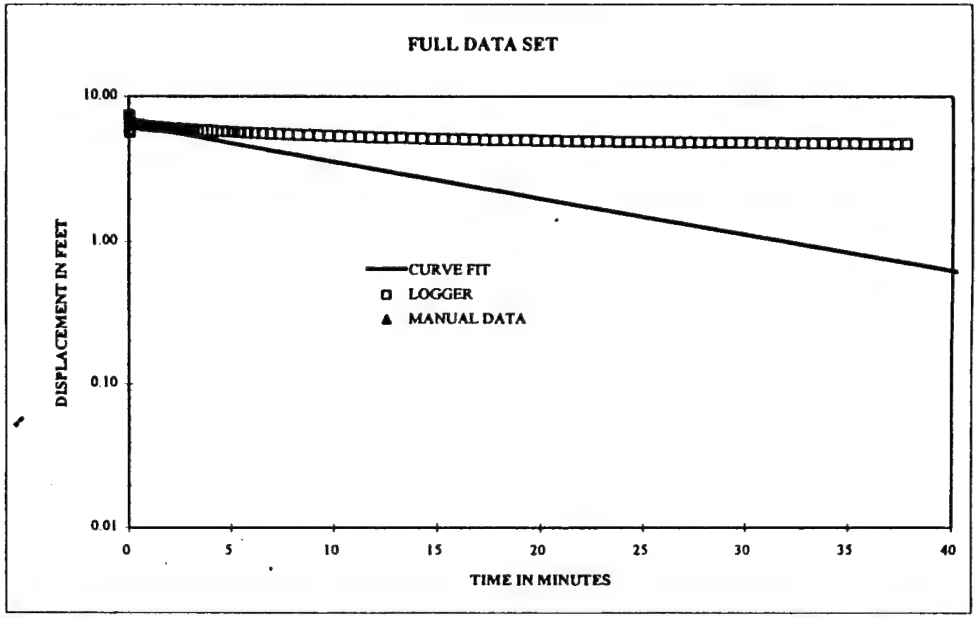
3.78E-05	cm/sec
7.43E-05	ft/min
0.11	ft/day

Casing stickup	1.60	feet
Static water level (from top of casing)	12.42	feet
Depth to bottom of screen (from ground level)	30.40	feet
Boring diameter	8.25	inches
Casing diameter	2.00	inches
Screen diameter	2.00	inches
Screen length	10.00	feet
Depth to "impermeable boundary"	50.00	feet
Porosity of filter pack	0.20	
Slug diameter (optional)		inches
Slug length (optional)		feet
Theoretical ΔH at time zero (Y_0)	0.00	feet
Actual ΔH at time zero (Y_0)	6.500	feet
ΔH at time t (Y_t)	1.500	feet
Time	25.00	min

Bouwer-Rice Parameters

feet	cm		cm	
10.82	329.79	*SW*		
19.58	596.80	*H*	120.00	*L/Rw*
20.4	621.79	*Ts*	0.50	*H/D*
0.083	2.54	*Rw*	4.60	*A*
0.083	2.54	*Rc*	0.75	*B*
0.167	5.08	*DS*	4.60	*C*
10.00	304.80	*L*	5.46	*Ln[(D-H)/Rw]'*
39.18	1194.21	*D*	5.46	*Ln[(D-H)/Rw]*
6.50000007	198.12	Y_0	3.65	equation (8)
1.5	45.72	Y_t	4.17	equation (9)
	1500.00	*t (seconds)*	3.65	*Ln(Re/Rw)*
	0.20	*n*	3.8E-05	equation (5)





Bouwer, Herman. 1989. "The Bouwer and Rice Slug Test - An Update". Ground Water vol. 27, no. 3, May-June 1989.

Bouwer, H. and R.C. Rice. 1976. A Slug Test for Determining Hydraulic Conductivity of Unconfined Aquifers [illegible]letely or Partially Penetrating Wells". Water Resources Research. vol 12, no. 3, June 1976.

AnalST

6/8/99

Client: **F.E. Warren AFB**

Project: **Landfill 3**

Project No.: **722450.3005**

Well No.: **PES-6D**

Test Date: **May 7, 1999**

Formation Tested:

Rising (R) or Falling (F) Head Test: **Falling - 1st Test**

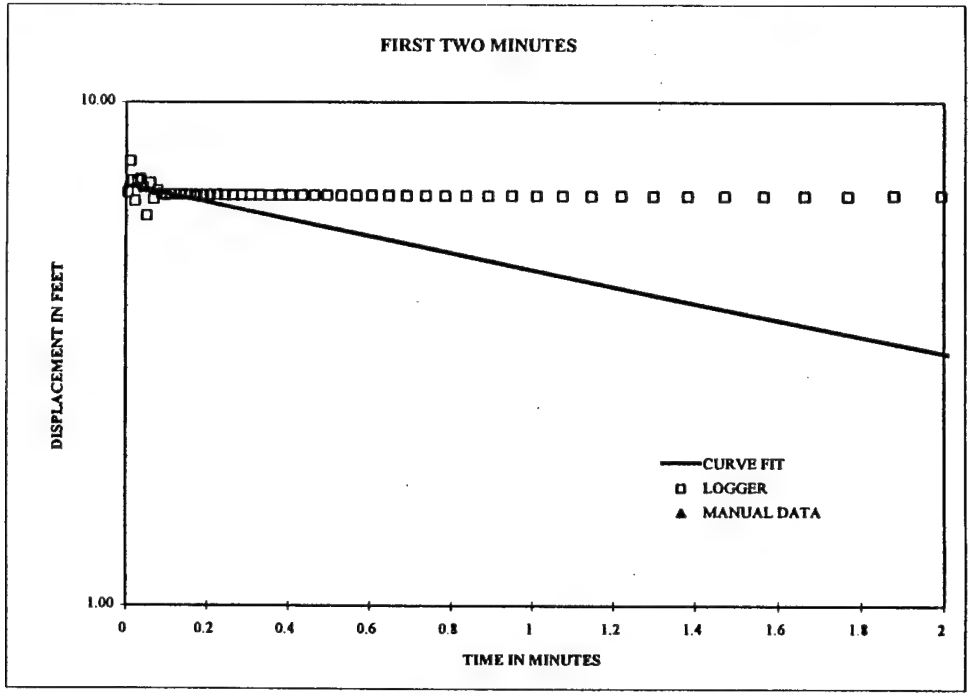
Logger Data File:

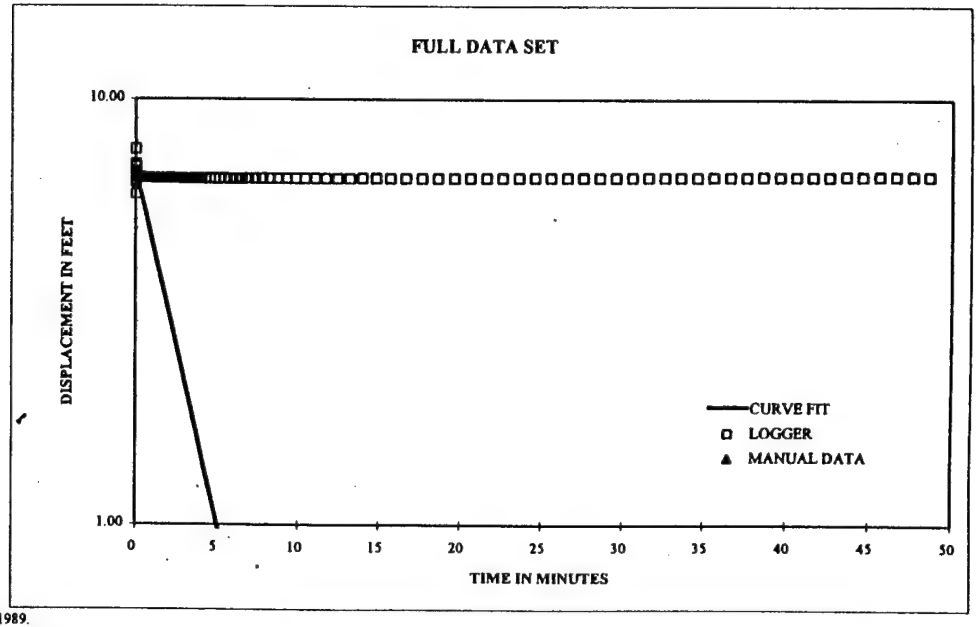
Hydraulic conductivity	4.85E-04	cm/sec
	9.54E-04	ft/min
	1.37	ft/day

Casing stickup	1.71	feet
Static water level (from top of casing)	14.19	feet
Depth to bottom of screen (from ground level)	42.79	feet
Boring diameter	8.25	inches
Casing diameter	2.00	inches
Screen diameter	2.00	inches
Screen length	5.00	feet
Depth to "impermeable boundary"	50.00	feet
Porosity of filter pack	0.20	
Slug diameter (optional)		inches
Slug length (optional)		feet
Theoretical ΔH at time zero (Y_0)	0.00	feet
Actual ΔH at time zero (Y_0)	6.900	feet
ΔH at time t (Y_t)	0.150	feet
Time	10.00	min

Bouwer-Rice Parameters

feet	cm		cm	
12.48	380.39	*SW*		
30.31	923.85	*H*	60.00	*L/Rw*
37.79	1151.84	*Ts*	0.81	*H/D*
0.083	2.54	*Rw*	3.30	*A*
0.083	2.54	*Rc*	0.50	*B*
0.167	5.08	*DS*	2.90	*C*
5.00	152.40	*L*	4.46	*Ln[(D-H)/Rw]'*
37.52	1143.61	*D*	4.46	*Ln[(D-H)/Rw]*
6.90000007	210.31	Y_e	3.59	equation (8)
0.15	4.57	Y_t	4.26	equation (9)
	600.00	*t (seconds)*	3.59	*Ln(Re/Rw)*
	0.20	*n*	4.8E-04	equation (5)





Bouwer, Herman. 1989. "The Bouwer and Rice Slug Test - An Update". Ground Water vol. 27, no. 3, May-June 1989.

Bouwer, H. and R.C. Rice. 1976. A Slug Test for Determining Hydraulic Conductivity of Unconfined Aquifers With Completely or Partially Penetrating Wells". Water Resources Research. vol 12, no. 3, June 1976.

Client: **F.E. Warren AFB**

Project: **Landfill 3**

Project No.: **722450.3005**

Well No.: **PES-6D**

Test Date: **May 7, 1999**

Formation Tested:

Rising (R) or Falling (F) Head Test: **Rising - 1st Test**

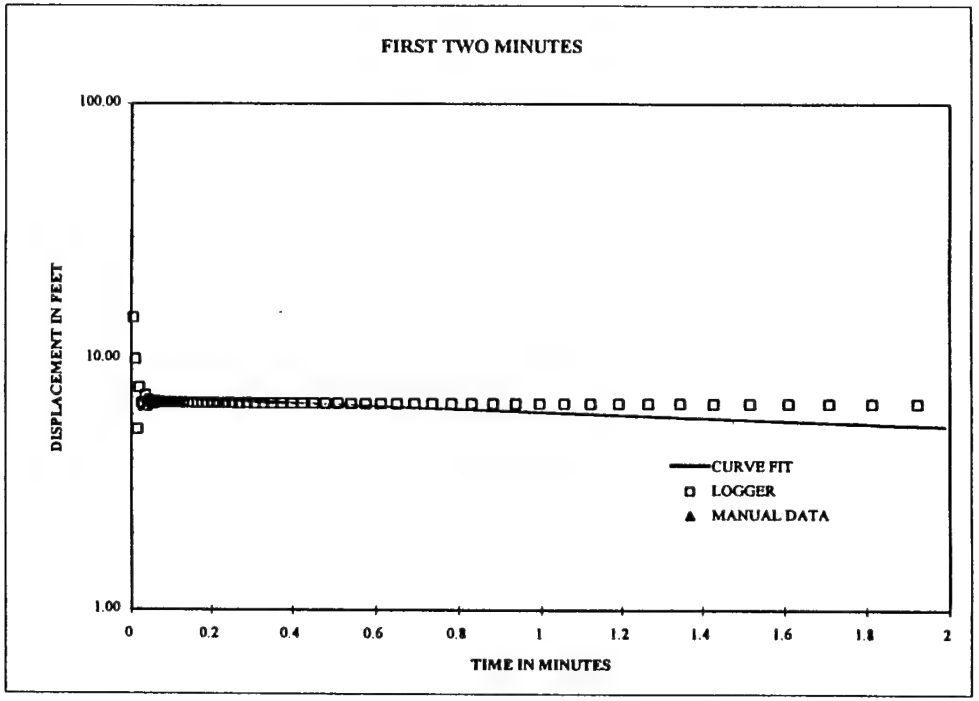
Logger Data File:

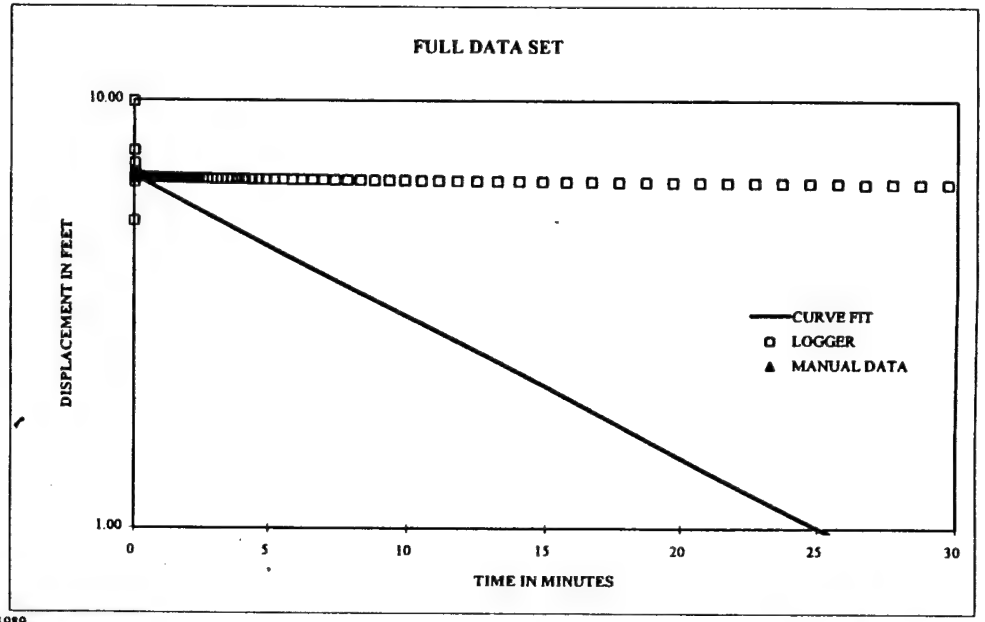
Hydraulic conductivity	9.62E-05	cm/sec
	1.89E-04	ft/min
	0.27	ft/day

Casing stickup	1.71	feet
Static water level (from top of casing)	14.19	feet
Depth to bottom of screen (from ground level)	42.79	feet
Boring diameter	8.25	inches
Casing diameter	2.00	inches
Screen diameter	2.00	inches
Screen length	5.00	feet
Depth to "impermeable boundary"	50.00	feet
Porosity of filter pack	0.20	
Slug diameter (optional)		inches
Slug length (optional)		feet
Theoretical ΔH at time zero (Y_0)	0.00	feet
Actual ΔH at time zero (Y_0)	6.700	feet
ΔH at time t (Y_t)	0.150	feet
Time	50.00	min

Bouwer-Rice Parameters

feet	cm		cm	
12.48	380.39	*SW*		
30.31	923.85	*H*	60.00	*L/Rw*
37.79	1151.84	*Ts*	0.81	*H/D*
0.083	2.54	*Rw*	3.30	*A*
0.083	2.54	*Rc*	0.50	*B*
0.167	5.08	*DS*	2.90	*C*
5.00	152.40	*L*	4.46	*Ln[(D-H)/Rw]'*
37.52	1143.61	*D*	4.46	*Ln[(D-H)/Rw]*
6.70000007	204.22	Y_o	3.59	equation (8)
0.15	4.57	Y_t	4.26	equation (9)
	3000.00	*t (seconds)*	3.59	*Ln(Re/Rw)*
	0.20	*n*	9.6E-05	equation (5)





Bouwer, Herman. 1989. "The Bouwer and Rice Slug Test - An Update". Ground Water vol. 27, no. 3, May-June 1989.

Bouwer, H. and R.C. Rice. 1976. A Slug Test for Determining Hydraulic Conductivity of Unconfined Aquifers [illegible]pletely or Partially Penetrating Wells". Water Resources Research. vol 12, no. 3, June 1976.

Anal ST[illegible] . 6/8/99

Client: **F.E. Warren**

Project: **Landfill 3**

Project No.: **722450.3005**

Well No.: **PES-6D**

Test Date: **May 10, 1999**

Formation Tested:

Rising (R) or Falling (F) Head Test: **Rising**

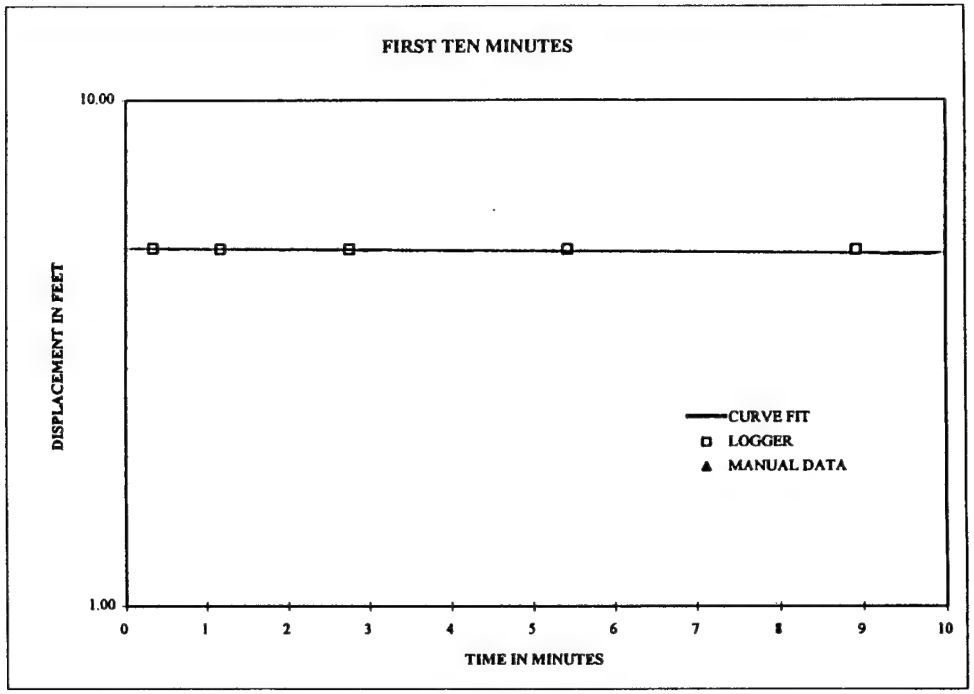
Logger Data File:

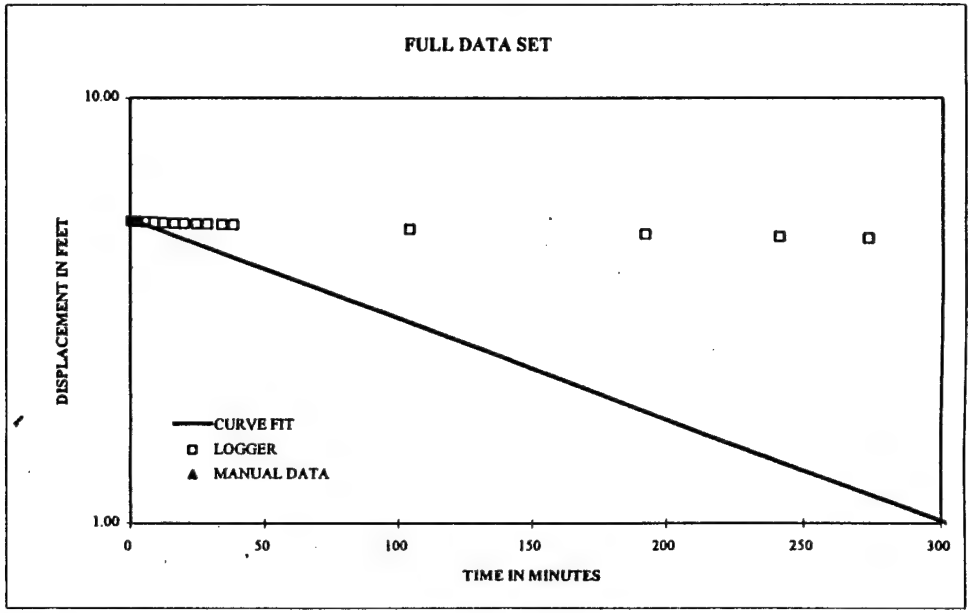
Hydraulic conductivity	6.89E-06	cm/sec
	1.36E-05	ft/min
	0.02	ft/day

Casing stickup	1.71	feet
Static water level (from top of casing)	14.19	feet
Depth to bottom of screen (from ground level)	42.79	feet
Boring diameter	8.00	inches
Casing diameter	2.00	inches
Screen diameter	2.00	inches
Screen length	5.00	feet
Depth to "impermeable boundary"	50.00	feet
Porosity of filter pack	0.20	
Slug diameter (optional)		inches
Slug length (optional)		feet
Theoretical ΔH at time zero (Y_0)	0.00	feet
Actual ΔH at time zero (Y_0)	5.200	feet
ΔH at time t (Y_t)	1.750	feet
Time	200.00	min

Bouwer-Rice Parameters

feet	cm		cm	
12.48	380.39	*SW*		
30.31	923.85	*H*	60.00	*L/Rw*
37.79	1151.84	*Ts*	0.81	*H/D*
0.083	2.54	*Rw*	3.30	*A*
0.083	2.54	*Rc*	0.50	*B*
0.167	5.08	*DS*	2.90	*C*
5.00	152.40	*L*	4.46	*Ln[(D-H)/Rw]'*
37.52	1143.61	*D*	4.46	*Ln[(D-H)/Rw]*
5.2	158.50	Y_0	3.59	equation (8)
1.75	53.34	Y_t	4.26	equation (9)
	12000.00	*t (seconds)*	3.59	*Ln(Re/Rw)*
	0.20	*n*	6.9E-06	equation (5)





Bouwer, Herman. 1989. "The Bouwer and Rice Slug Test - An Update". Ground Water vol. 27, no. 3, May-June 1989.

Bouwer, H. and R.C. Rice. 1976. A Slug Test for Determining Hydraulic Conductivity of Unconfined Aquifers With Completely or Partially Penetrating Wells". Water Resources Research. vol 12, no. 3, June 1976.

99137

Parsons Eng.

Mon. to - Wells

FEW

5/20/99

JBJ

BJS

NATIONAL PRINTRAST NO. 446

Vote Elev
[illegible] NAVD 29
Based on Nob Hill

STA	+	HI	-	Elev	
B.M				614.62	
	8.17	22.79			
				NGVD29	NAVD88
MW 5D PVC			3.59	19.20	22.52
Ground			5.7	17.09	20.41
Cone			5.28	17.51	20.83
	6.12	23.63			
MW203BC			6.12	17.51	
TP			2.65	20.98	
	7.56	28.54			
MW206 BC			4.06	24.48	
MW 3D PVC			1.63	26.91	30.23
Ground			4.0	24.54	27.86
Cone			3.68	24.86	28.18
	6.14	31.00			
TP Nail			1.99	29.01	

6"X6" Cone Mon North
& PT Nob Hill Subd.

ADD
3.32
To All
Elev
To get
To NAVD 88

NATIONAL PRINTFAST NO. 446

Sta	+	HI	−	Elev
TPN:11 (west)			~~29.01~~	29.01
	1.39	30.40		
+P			13.37	17.03
	2.06	19.09		
TP Nail (East Gate)			9.08	10.01
	8.29	18.30		
B.M.			3.68	14.62
			S/C	14.62

NATIONAL PRINTAST NO. 446

Sta		HI	—	Elev	
TPNA12 East				6/10/01	
	5.47	15.48			
				NGVD 29	NAVD88
MW6S PVC			3.69	11.79	15.11
Ground			5.6	9.88	13.20
Conc			5.29	10.19	13.51
	5.35	15.54			
MW6D PVC			3.73	11.81	15.13
Ground			5.9	9.64	12.96
Conc			5.44	10.10	13.42
	10.08	20.18			
TP			1.26	18.92	
	13.22	32.14			
MW4D PVC			1.21	30.93	34.26
Ground			3.4	28.74	32.06
Conc			3.04	29.10	32.42
	10.90	40.00			
Ni 147 Conc			10.95	29.05	
MW2D PVC			0.51	39.49	42.81
Ground			2.4	37.6	40.92
Conc			2.14	37.86	41.18

NATIONAL PRINTRAST NO. 446

STA	+	AI	-	E/PV NGVD.29	NAVD88
MW 2D Conc				37.86	
	11.70	49.56			
MW 62 Conc			11.93	37.63	
MW 15 PVC			1.31	48.25	51.57
Ground			3.3	46.26	49.58
Conc			2.80	46.76	50.08
	1.05	47.81			
~~TP Nail~~ West					
TP			15.43	32.38	
MW 209 B.C	4.51	36.89			
TP Nail-1 West			7.88	29.01	
			s/b	6129.01	

NATIONAL PRINTFAST NO. 446

Project name : C:\TSOffice\Projects\99137 PARSONS FEW
Description : USFeet Template
Coordinate System : Projection from data collector
Zone : Zone from data collector
Datum : WGS-84
Date printed : 5/21/99 6:36:05 AM

Coordinate units: US survey feet
Elevation units: US survey feet

Point listing

Name	Northing	Easting	Elevation	Feature code
1	231277.131	739102.668	6181.770	CP GPS BASE
1	231277.132	739102.668	6181.770	CP GPS BASE
10	232122.606	744144.697	6113.405	MW PES-6D
11	232118.658	744136.167	6113.458	MW PES-6S
12	231946.451	743463.330	6132.364	MW PES-4D
13	231786.480	743174.247	6141.171	MW PES-2D
14	231530.330	742977.486	6150.039	MW PES-1S
15	231392.159	743388.246	6128.133	MW PES-3D
16	231626.952	743941.529	6120.799	MW PES-5D
123	230547.981	750029.362	6065.531	CP STEIL

APPENDIX C

LABORATORY ANALTYICAL DATA

MEMORANDUM

MANTECH ENVIRONMENTAL RESEARCH SERVICES CORP.
Environmental Science

In reply refer to: 99/JAD35
Contract # 68-c-98-138

To: Dr. Don Kampbell

Thru: Dr. Dennis Fine DF

From: John Daniel JAD

Subject: SF-0-71

Date: June 2, 1999

Copies: R.L Cosby
G.B. Smith
J. L. Seeley JS

As requested in Service Request # SF-0-71, headspace GC/MS analysis of 36 water samples from Warren AFB for choroethene volatiles was completed. The samples were received May 11, 1999 and analyzed on May 27-28, 1999. RSKSOP-148 (Determination of Volatile Organic Compounds in Water by Automated Headspace Gas Chromatography/Mass Spectrometry (Saturn II Ion Trap Detector) was used for this analysis.

An internal standard calibration method was established for 16 compounds. The standard curves were prepared from 1.0 to 10000 ppb.

A dilution corrected quantitation report for the samples, lab duplicates, field duplicates, QCs, standards and lab blank is presented in tables 1-2.

If you should have any questions, please feel free to contact me.

Table I. Quantitative Report fo[redacted]F-0-71 Warren AFB.

Date received = 5/11/99 | Originator = Dr. Don Kampbell | Date analyzed = 5/27-28/99

Concentration ppb

Compound Sample Name:	MW-62	MW-64	MW-147	MW-147 Field Dup	196A	196B	197	MW-198	MW-199D	MW-199M
VINYL CHLORIDE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
1,1-DICHLOROETHENE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
T-1,2-DICHLOROETHENE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
1,1-DICHLOROETHANE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
C-1,2-DICHLOROETHENE	—	ND	6.1	5.6	ND	ND	ND	ND	ND	ND
CHLOROFORM	—	2.3	—	—	1.0	ND	ND	—	ND	ND
1,1,1-TRICHLOROETHANE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
CARBON TETRACHLORIDE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
1,2-DICHLOROETHANE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
TRICHLOROETHENE	—	ND	10.3	10.5	ND	ND	ND	ND	ND	ND
TETRACHLOROETHENE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
CHLOROBENZENE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
1,3-DICHLOROBENZENE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
1,4-DICHLOROBENZENE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
1,2-DICHLOROBENZENE	ND	ND	ND	ND	ND	ND	ND	—	ND	ND

	MW-199S	MW-199S Lab Dup	MW201	MW-203	MW-206	MW-207	MW-208	MW-209	MW-209D	MW-209M
VINYL CHLORIDE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
1,1-DICHLOROETHENE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
T-1,2-DICHLOROETHENE	ND	ND	ND	ND	ND	1.7	—	5.7	ND	1.3
1,1-DICHLOROETHANE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
C-1,2-DICHLOROETHENE	ND	ND	ND	5.1	1.2	34.9	22.8	129	ND	50.0
CHLOROFORM	ND	ND	ND	ND	ND	—	—	—	ND	—
1,1,1-TRICHLOROETHANE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
CARBON TETRACHLORIDE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
1,2-DICHLOROETHANE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
TRICHLOROETHENE	ND	ND	—	12.8	2.6	33.1	23.0	93.1	ND	76.2
TETRACHLOROETHENE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
CHLOROBENZENE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
1,3-DICHLOROBENZENE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
1,4-DICHLOROBENZENE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
1,2-DICHLOROBENZENE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

	MW-209M Field Dup	MW-210	MW-210D	MW-210D Lab Dup	MW210M	MW-211	MW-232	MW-233	MW-236	MW-237
VINYL CHLORIDE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
1,1-DICHLOROETHENE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
T-1,2-DICHLOROETHENE	1.2	—	ND	ND	ND	ND	ND	ND	ND	ND
1,1-DICHLOROETHANE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
C-1,2-DICHLOROETHENE	49.6	15.8	ND	ND	6.9	3.3	ND	ND	ND	ND
CHLOROFORM	—	—	ND	ND	ND	—	—	ND	ND	ND
1,1,1-TRICHLOROETHANE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
CARBON TETRACHLORIDE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
1,2-DICHLOROETHANE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
TRICHLOROETHENE	77.9	26.7	ND	ND	18.3	7.5	ND	—	—	ND
TETRACHLOROETHENE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
CHLOROBENZENE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
1,3-DICHLOROBENZENE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
1,4-DICHLOROBENZENE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
1,2-DICHLOROBENZENE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

ND = None Detected — = Below Calibration Limit(1.0 ppb) Dup = Duplicate

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Table 2. Quantitative Report for S.R. # SF-0-71 Warren AFB.

Date received = 5/11/99

Originator = Dr. Don Kampbell
Concentration ppb

Date analyzed = 5/27-28/99

	MW-237 Field Dup	MW-238	PES-15	PES-2D	PES-3D	PES-3D Lab Dup	PES-4D	PES-5D	PES-6D	PSE-6S
VINYL CHLORIDE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
1,1-DICHLOROETHENE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
T-1,2-DICHLOROETHENE	ND	ND	1.6	ND	ND	ND	ND	ND	ND	ND
1,1-DICHLOROETHANE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
C-1,2-DICHLOROETHENE	ND	ND	31.9	2.3	ND	ND	3.0	1.3	ND	2.5
CHLOROFORM	ND	2.3	—	1.0	ND	ND	ND	ND	ND	ND
1,1,1-TRICHLOROETHANE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
CARBON TETRACHLORIDE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
1,2-DICHLOROETHANE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
TRICHLOROETHENE	ND	1.1	33.9	4.3	—	—	12.3	3.3	ND	11.0
TETRACHLOROETHENE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
CHLOROBENZENE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
1,3-DICHLOROBENZENE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
1,4-DICHLOROBENZENE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
1,2-DICHLOROBENZENE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

	Field Blank	LF-03	QC0527A 20 ppb	QC0527B 200 ppb	QC0527C 20 ppb	QC0527D 200 ppb	QC0527E 20 ppb	QC0527F 200 ppb	QC0527G 20 ppb	BL0527A
VINYL CHLORIDE	ND	ND	20.4	190	20.1	216	19.6	199	21.5	ND
1,1-DICHLOROETHENE	ND	ND	18.3	173	17.8	202	17.9	183	18.5	ND
T-1,2-DICHLOROETHENE	ND	ND	19.7	184	19.3	195	18.5	183	18.6	ND
1,1-DICHLOROETHANE	ND	ND	NI	NI	NI	NI	NI	NI	NI	ND
C-1,2-DICHLOROETHENE	ND	ND	20.3	204	20.2	192	19.1	198	20.3	ND
CHLOROFORM	ND	ND	NI	NI	NI	NI	NI	NI	NI	ND
1,1,1-TRICHLOROETHANE	ND	ND	19.1	191	20.0	217	20.1	202	20.1	ND
CARBON TETRACHLORIDE	ND	ND	17.5	172	18.3	203	18.1	187	18.7	ND
1,2-DICHLOROETHANE	ND	ND	20.9	211	21.4	176	21.0	206	21.1	ND
TRICHLOROETHENE	ND	ND	17.4	184	17.9	196	17.7	181	18.2	ND
TETRACHLOROETHENE	ND	ND	19.0	183	18.8	205	18.8	190	18.9	ND
CHLOROBENZENE	ND	ND	20.8	205	20.2	210	19.5	208	20.2	ND
1,3-DICHLOROBENZENE	ND	ND	NI	NI	NI	NI	NI	NI	NI	ND
1,4-DICHLOROBENZENE	ND	ND	20.8	214	20.6	212	19.7	212	20.6	ND
1,2-DICHLOROBENZENE	ND	ND	20.6	210	19.8	201	20.5	206	20.3	ND

ND = None Detected — = Below Calibration Limit(1.0 ppb) Dup = Duplicate QC = Quality Control Std NI = Not included in QC

MANTECH

MEMORANDUM
MANTECH ENVIRONMENTAL RESEARCH SERVICES CORP.
Environmental Sciences

In reply refer to: 99-MB20

To: Dr. Don Kampbell

From: Mark Blankenship MB

THRU: Dr. Dennis Fine

Date: May 17, 1999

Copies: R.L. Cosby
G.B. Smith
J.L. Seeley JLS

Please find attached the analytical results for Service Request SF-0-71 requesting the analysis of Warren AFB, WY ground water samples to be analyzed for BTEXXX, TMB's and MTBE. The samples were collected May 3, 1999 through May 6, 1999. We received a total of 36 samples, in duplicate, in capped, 40 mL VOA vials on May 11, 1999. Samples were analyzed May 13 and May 14, 1999. The samples were acquired and processed using the Millennium data system. A 5 point (1-1000 ppb) external calibration curve was used to determine the concentration for for all compounds.

RSKSOP-122 " Analysis of Volatile Aromatic Hydrocarbons with Separation of Xylene Isomers by Purge and Trap Gas Chromatography" was used for these analyses. Autosampling was performed using a Dynatech Precision autosampler system in line with a Tekmar LSC 2000 concentrator.

[redacted] 5/17/99 SF-0-71 Warren AFB, WY [redacted]s for Dr.Kampbell Units = ng/ml [redacted] M. Blankenship

SAMPLE NAME	MTBE	BENZENE	TOLUENE	ETHYLBENZENE	p-XYLENE	m-XYLENE	o-XYLENE	1,3,5-TMB	1,2,4-TMB	1,2,3-TMB
10 PPB STD	8.7	9.3	9.9	10.5	9.9	10.2	9.5	10.6	10.1	9.4
20 PPB QA\QC	18.3	19.5	19.2	19.7	19.9	20.4	18.8	21.1	20.5	18.2
MW-62	ND	BLQ	BLQ	ND	ND	BLQ	BLQ	ND	ND	ND
MW-64	ND	ND	BLQ	ND	ND	BLQ	ND	BLQ	ND	ND
MW-147	ND	ND	BLQ	BLQ	BLQ	ND	ND	ND	ND	ND
MW-196A	ND	ND	BLQ	ND	ND	BLQ	ND	ND	ND	ND
MW-196B	ND	ND	BLQ	BLQ	ND	BLQ	ND	ND	ND	ND
MW-197	ND	ND	ND	ND	ND	ND	BLQ	BLQ	ND	ND
MW-198	ND	ND	BLQ	ND	ND	ND	BLQ	BLQ	ND	ND
MW-198 LAB DUPLICATE	ND	ND	BLQ	ND	ND	ND	ND	BLQ	ND	ND
MW-199D	ND	ND	BLQ	ND	ND	ND	ND	BLQ	ND	ND
MW-199M	BLQ	ND	ND	ND	BLQ	ND	ND	ND	ND	ND
MW-199S	ND	ND	BLQ	ND	BLQ	BLQ	ND	BLQ	ND	ND
10 PPB STD	9.2	9.3	9.8	10.2	9.7	9.9	9.7	10.3	9.9	9.5
MW-201	ND	ND	BLQ	BLQ	ND	BLQ	ND	ND	ND	ND
MW-203	ND	ND	BLQ	ND	ND	BLQ	ND	ND	ND	ND
MW-206	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
MW-207	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
MW-208	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
MW-209	ND	ND	BLQ	ND	ND	ND	ND	ND	ND	ND
MW-209D	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
MW-209D LAB DUPLICATE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
MW-209M	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
MW-210	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
MW-210D	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
20 PPB QA\QC	17.9	17.9	19.0	19.4	19.6	19.6	19.2	21.1	20.7	19.0

ND = None Detected; BLQ = Below Limit of Quantitation, 1 ppb.

Sampled 5/3/99 thru 5/6/99

Analyzed 5/13/99 and 5/14/99

Printed 5/17/99 SF-0-71 Warren AFB, WY

Analyses for Dr.Kampbell

Units = ng/ml Analyst M. Blankenship

SAMPLE NAME	MTBE	BENZENE	TOLUENE	ETHYLBENZENE	p-XYLENE	m-XYLENE	o-XYLENE	1,3,5-TMB	1,2,4-TMB	1,2,3-TMB
MW-210M	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
MW-211	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
MW-232	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
MW-233	ND	ND	BLQ	ND	ND	ND	ND	ND	ND	ND
100 PPB STD	92.7	91.2	97.2	106.1	104.5	104.1	98.6	102.9	107.9	100.7
MW-236	BLQ	BLQ	BLQ	ND	BLQ	BLQ	ND	ND	ND	ND
MW -237	ND	ND	ND	BLQ	BLQ	BLQ	BLQ	ND	ND	ND
MW-238	ND	ND	BLQ	1.2	BLQ	BLQ	ND	ND	ND	ND
PES-1S	ND	ND	ND	ND	BLQ	ND	ND	ND	ND	ND
PES-1S LAB DUPLICATE	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
PES-2D	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
PES-3D	1.4	ND	ND	ND	BLQ	BLQ	ND	ND	ND	ND
PES-4D	BLQ	ND	ND	2.1	ND	BLQ	BLQ	ND	ND	ND
PES-5D	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
PES-6D	ND	ND	BLQ	BLQ	BLQ	ND	ND	BLQ	ND	ND
PES-6S	ND	ND	ND	ND	BLQ	BLQ	ND	ND	ND	ND
100 PPB STD	99.4	94.8	102.2	109.3	107.4	106.5	101.5	105.7	101.9	103.7
FIELD BLANK	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
LF-03	ND	ND	2.0	ND	ND	ND	ND	ND	ND	ND

ND = None Detected; BLQ = Below Limit of Quantitation, 1 ppb,

Sampled 5/3/99 thru 5/6/99

Analyzed 5/[illegible]9 and 5/14/99

MEMORANDUM
MANTECH ENVIRONMENTAL RESEARCH SERVICES CORP
Environmental Science

In reply refer to : 99-SH48
Contract #68-C-99-138

To: Dr. Don Kampbell . From: Sharon Hightower SH

Thru: Dennis Fine DFine

Subject: SF-0-91 Date: May 12, 1999

Copies: R.L. Cosby
G.B. Smith
J.L. Seeley JS
L.K. Pennington LKP

Attached are TOC results for 34 Warren samples submitted May 11, 1999 under Service Request #SF-0-91. Sample analysis was begun May 11, 1999 and completed May 11, 1999 using RSKSOP-102.

Blanks, duplicates, and AQC samples were analyzed along with your samples, as appropriate, for quality control. If you have any questions concerning this data, please feel free to ask me.

ManTech Environmental Research Services Corporation

R.S. Kerr Environmental Research Center, P.O. Box 1198, 919 Kerr Research Drive
Ada, Oklahoma 74821-1198 580-436-8660 FAX 580-436-8501

KAMPBELL WARREN LIQUIDS SF-0-91
SAMPLES RECEIVED 5/11/99
SAMPLES ANALYZED 5/12/99 BY SHARON HIGHTOWER

SAMPLE	MG/L TOC
PES-1S, 5/6	32.3
PES-2D, 5/6	11.9
PES-3D, 5/6	9.72
PES-4D, 5/5	31.5
PES-5D, 5/6	38.0
PES-6D, 5/6	1.56
PES-6S, 5/5	3.18
MW-62, 5/6	3.34
MW-64, 5/4	3.98
MW-147, 5/5	5.45
MW-196A, 5/4	39.4
MW-196B, 5/4	1.93
DUP	1.93
WP40	24.3
MW-197, 5/3	19.1
MW-198, 5/4	4.18
MW-199D, 5/3	.800
MW-199M, 5/3	1.03
MW-199S, 5/3	9.79
MW-201, 5/4	14.9
MW-203, 5/5	14.7
MW-206, 5/5	5.81
DUP	5.94
WP40	25.0
5 MG/L	5.85
MW-207, 5/5	7.31
MW-208, 5/5	7.93
MW-209, 5/5	7.81
MW-209D, 5/5	2.16
MW-209M, 5/5	5.52
MW-210, 5/5	6.03
MW-210D, 5/5	4.60
MW-210M, 5/5	5.17
MW-211, 5/5	6.84
MW-232, 5/5	3.24
DUP	3.18
WP40	24.6
MW-233, 5/4	4.52
MW-236, 5/4	6.45
MW-237, 5/4	24.6
MW-238, 5/4	9.42
5 MG/L	5.71
WP40	24.7
BLANK	<.4

WP40 std. t.v.=24.0 +/- 2.40

MEMORANDUM

MANTECH ENVIRONMENTAL RESEARCH SERVICES CORP.
Environmental Science

In reply refer to: 99-DK3/vg

To: Dr. Don Kampbell

From: David Kovacs DAK

Thru: D.D. Fine

Date: May 26, 1999

Subject: Service Request #SF-0-91

Ref:

Copies: R.L. Cosby
G.B. Smith
J.L. Seeley

Contract # 68-C-98-138

This report contains the results of my GC/MS analysis of samples from Warren AFB, under Service Request SF-0-91. The samples were extracted with m-xylene for quantitation of the following volatile halocarbons, using selected ion monitoring (SIM) mass spectrometry: vinyl chloride; 1,1-dichloroethene (1,1-DCE); t-dichloroethene (t-DCE); c-dichloroethene (c-DCE); trichloroethene (TCE) and tetrachloroethene (PCE). The samples were also extracted with methylene chloride for quantitation of the following target compounds, using selected ion monitoring (SIM) mass spectrometry: trichloroethene (TCE); tetrachloroethene (PCE); benzene; toluene; ethylbenzene (EB); p-xylene (p-X); m-xylene (m-X); o-xylene (o-X); 1,3,5-trimethylbenzene (1,3,5-TMB); 1,2,4-trimethylbenzene (1,2,4-TMB); 1,2,3-trimethylbenzene (1,2,3-TMB); naphthalene (N); 2-methylnaphthalene (2-MN); 1-methylnaphthalene (1-MN).

The analytical method was a modification of RSKSOP-124. For the methylene chloride extracts, cool on-column injection (0.1 µl) was used with electronic pressure control set for a constant flow of 1.0 ml/min. The capillary GC column consisted of a 30m X 0.25mm Restek Stabilwax (Crossbonded Carbowax-PEG, 0.5um film) plus an SGE 0.1m X 0.53 mm ID uncoated capillary precolumn. Calibration standards ranged from 0.025 to 250 µg/ml at decade intervals. For the m-xylene extracts the quantitative range was 0.2 to 200 ug/ml at decade intervals. A J&W Scientific DB-624 capillary column (30m X 0.25mm X 1.4um film thickness) plus an SGE 0.1m X 0.53 mm ID uncoated capillary precolumn was used for gas chromatographic separation. A 0.1 µl volume was injected on-column. For all analyses SIM mode GC/MSD was used with the ions chosen from those listed in EPA method 524.2 Revision 3.0, where available. Multiple ions were acquired and ion ratios used to verify the accuracy of target compound identification. For both the methylene chloride and m-xylene extracts quality control standard mixtures, prepared by a different source than the

calibration standards, were analysed to assure the accuracy of quantitation. Complete reports detailing the acquisition method and calibration curves have been recorded.

The samples were received May 11, 1999. The methylene chloride extractions (5.0 gram soil) were performed May 12, 1999 and m-xylene extractions performed on May 13, 1999. Methylene chloride and m-xylene extracts were analyzed by scan and SIM mode GC/MSD between May 16 and May 20, 1999. The methylene extraction method was similar to that described in RSKSOP-72 and the x-xylene extraction followed the procedure described in the report delivered to Barbara Wilson describing the m-xylene extraction technique (Ref: #96-DK29/vg, dated May 29, 1996). Additional details about the m-xylene extract method are contained in another report to Barbara Wilson (Ref: #96-DK32/vg, dated July 8, 1996).

Special note regarding the m-xylene extracts for halocarbons:
The m-xylene extraction procedure includes a step where the samples are frozen, following mixing, to break down the xylene/water emulsion. While not normally a problem, in this case, 5 of the 8 sample extracts were lost because the VOA vials cracked during freezing. The lost samples were PES-1S 32', PES 2D 22', PES 3D, PES 4D 20-22', PES 6D 30'. In response to this problem, I have run tests to determine the cause of the glass vial failure. I have contacted the VOA vial supplier , OEC (Quality Environmental Containers, P.O. Box 1160, Beaver, WV 25813, phone 800/255-3950) and have found that the vials we used are their "highest quality". They sent me a new case of vials and I freeze-tested the lot of vials we used for your extractions (product #2112), vials from their new box (product #2112) and vials, used previously, that had performed well without cracking (Supelco #2-7089, Lot: 091197). The results of this test (9 QEC vials and 6 Supelco vials) indicate clearly that the QEC vials are of an inferior quality (weaker glass) for this application. 5 of 9 QEC vials cracked during freezing while none of the Supelco vials cracked. The QEC vials used for your samples were obtained from the Kerr Lab supply room as a normal inventory item. In the future, I will use the Supelco vials or one of equal or superior quality. I would recommend that the stockroom consider changing the VOA vial it normally stocks to a thicker, higher quality glass. Returning to a higher quality VOA vial may prevent additional sampling problems, for others, in the future.

If you require further information, please feel free to contact me.

Results:
Units = ug/g wet weight soil

Methylene Chloride Extracts

PES-1S-32'	None Detected
PES-1S-32' Dup.	None Detected
PES-2D-22'	None Detected
PES-3D	None Detected
PES-4D-20-22'	Benzene = 7.97 E-3
	PCE = 6.91 E-2
	Toluene = 4.78 E-2

All other target analytes = None Detected

PES-5D	None Detected
PES-6S-25'	None Detected
PES-6D-30'	None Detected

m-Xylene Extracts

PES-1S-32'	None Detected
PES-5D	None Detected
PES-6S-25'	None Detected

MANTECH

MEMORANDUM

MANTECH ENVIRONMENTAL RESEARCH SERVICES CORP.
Environmental Science

In reply refer to: 99-50LP/lp
99-54SH/lp
Contract # 68-C-98-138

To: Dr. Don Kampbell

Thru: D.D. Fine

From: Lynda Pennington LKP
Sharon Hightower SH

Subject: SR # SF-0-71

Ref:

Copies: R.L. Cosby
G.B. Smith
J.L. Seeley JLS

Date: May 27, 1999

Attached are inorganic results for 34 Warren AFB samples submitted to MERSC under Service Request # SF-0-71. The samples were received May 11, and were analyzed May 12, 1999. The methods used for analysis were Waters capillary electrophoresis method N-601 for chloride and sulfate and Lachat FIA methods 10-107-04-2-A for nitrate+ nitrite and 10-107-06-1 for ammonia.

Quality control measures performed along with your samples included analysis of blanks, duplicates, spikes, known WPO samples and check standards.

If you have any questions concerning this data, please feel free to contact us.

ManTech Environmental Research Services Corporation

R.S. Kerr Environmental Research Center, P.O. Box 1198, 919 Kerr Research Drive
Ada, Oklahoma 74821-1198 580-436-8660 FAX 580-436-8501

Rec'd 5-11-99
Analyzed 5-12-99 by
L. Pennington: Cl, SO4
S. Hightower: NO2+NO3; NH3

S.R. # SF-0-71
Don Kampbell
Warren AFB samples

SAMPLE	$NO_2^-+NO_3^-$ (N)	NH_3 (N)	Cl^-	SO_4^{-2}
	mg/L	mg/L	mg/L	mg/L
MW-62	7.65	<0.10	20.8	47.2
MW-64	6.50	<0.10	24.5	52.4
MW-147	9.17	<0.10	31.4	55.4
196-A	6.06	<0.10	43.2	40.3
196-B	(1.65) (1.64)	(<0.10) (<0.10)	2.54	16.2
MW-197	4.33	<0.10	(4.08) (3.99)	(136) (134)
MW-198	7.69	<0.10	26.6	38.3
MW-199D	0.82	<0.10	<0.50	7.66
MW-199M	0.83	<0.10	<0.50	9.51
MW-199S	5.68	<0.10	30.9	74.3
MW-201	17.8	<0.10	299	487
MW-203	8.49	<0.10	198	271
MW-206	6.29	<0.10	54.3	84.9
MW-207	0.98	0.99	(73.6) (73.0)	(140) (137)
MW-208	(19.5) (19.3)	(<0.10) (<0.10)	66.6	206
MW-209	18.7	<0.10	68.9	145
MW-209D	2.00	<0.10	2.13	11.4
MW-209M	17.9	<0.10	56.9	140
MW-210	11.3	<0.10	89.9	75.2
MW-210D	1.15	<0.10	1.38	18.5
MW-210M	7.18	<0.10	13.0	25.7
MW-211	8.18	<0.10	39.6	47.4
MW-232	5.65	<0.10	43.6	52.6
MW-233	16.6	<0.10	(26.9) (26.8)	(78.6) (78.4)
MW-236	12.3	<0.10	224	208
MW-237	(4.10) (4.17)	(<0.10) (<0.10)	56.8	135
MW-238	7.85	<0.10	102	285
PES-1S	19.3	<0.10	62.8	165
PES-2D	9.25	<0.10	28.8	53.2
PES-3D	3.81	<0.10	14.9	26.3
PES-4D	7.35	<0.10	13.7	27.3
PES-5D	4.44	<0.10	(134) (134)	(195) (194)
PES-6D	1.05	<0.10	1.26	19.6
PES-6S	6.79	<0.10	24.5	33.4
Blank	<0.10	<0.10	<0.50	<0.50
AQC	(12.0) (12.2)	(4.97) (4.84)	(10.7) (10.2)	(59.0) (57.2)
AQC T.V.	12.0	4.80	10.8	58.0
Check Std.	(0.97) (0.98)	(0.99) (0.97)	(4.98) (24.4)	(5.06) (24.3)
Check Std. T.V.	1.00	1.00	(5.00) (25.0)	(5.00) (25.0)
Spike Recovery	100%	99%	(101%) (100%)	(102%) (99%)

MANTECH ENVIRONMENTAL TECHNOLOGY

MEMORANDUM
MANTECH ENVIRONMENTAL RESEARCH SERVICES CORP
Environmental Science

In reply refer to : 99-SH51
Contract #68-C-99-138

To: Dr. Don Kampbell From: Sharon Hightower SH

Thru: Dennis Fine

Subject: SF-0-91 Date: May 20, 1999

Copies: R.L. Cosby
G.B. Smith
J.L. Seeley JS
L.K. Pennington LKP

Attached are TOC results for 8 Warren samples submitted May 12, 1999 under Service Request #SF-0-91. Sample analysis was begun May 12, 1999 and completed May 19, 1999 using Leco Method 203-601-272.

Blanks, duplicates, and AQC samples were analyzed along with your samples, as appropriate, for quality control. If you have any questions concerning this data, please feel free to ask me.

ManTech Environmental Research Services Corporation

R.S. Kerr Environmental Research Center, P.O. Box 1198, 919 Kerr Research Drive
Ada, Oklahoma 74821-1198 580-436-8660 FAX 580-436-8501

KAMPBELL WARREN SOIL SAMPLES SF-0-91
SAMPLES RECEIVED 5/12/99
SAMPLES ANALYZED 5/19/99 BY SHARON HIGHTOWER

SAMPLE	% TOC	MEAN % TOC	STD DEV.
PES-65-25, #1	.028	.027	.006
#2	.033		
#3	.021		
PES-40-22, #1	.025	.028	.003
#2	.028		
#3	.030		
PES-15-32, #1	.049	.038	.009
#2	.034		
#3	.032		
PES-20, #1	.032	.036	.008
#2	.045		
#3	.030		
PES-DUP-15-32, #1	.030	.024	.005
#2	.021		
#3	.023		
PES-5D, #1	.020	.018	.005
#2	.021		
#3	.012		
PES-3D, #1	.016	.019	.003
#2	.022		
#3	.020		
PES-6D-30, #1	.026	.026	.005
#2	.030		
#3	.020		
LECO STD.	.929		
LECO STD.	.928		
LECO STD.	.959		
LECO STD.	.985		

MANTECH

MEMORANDUM
MANTECH ENVIRONMENTAL RESEARCH SERVICES CORP.
Environmental Science

In reply refer to: 99-LH1
68-C-98-138

To: Dr. [redacted] Campbell

Thru: Dennis Fine

From: Lisa Hudson

Subject: SF-0-71

Date: July 20, 1999

Copies: R.L. Cosby
G.B. Smith
J.L. Seeley

As requested in Service Request #SF-0-71, gas analysis was performed for methane, ethylene and ethane from Warren AFB. The samples were received on May 11, 1999, and analyzed on July 19, 1999. Calculations were done as per RSKSOP-175. Analyses were performed as per RSKSOP-194.

If you have any questions concerning this data, please feel free to contact me.

ManTech Environmental Research Services Corporation

R.S. Kerr Environmental Research Center, P.O. Box 1198, 919 Kerr Research Drive
Ada, Oklahoma 74821-1198 580-436-8660 FAX 580-436-8501

Service Request: SF-0-71 **Originator: D. Kampbell** **Analyst: L. Hudson**

Site: Warren AFB

Sample Received: 5/11/1999 **Sampling Date: 5/4/99** **Sample Analyzed: 7/19/99**

Sample	Methane ppm (Gas)	Methane ppm mg/L(Water)	Ethylene ppm (Gas)	Ethylene ppm mg/L(Water)	Ethane ppm (Gas)	Ethane ppm mg/L(Water)
100 ppm CH4	98.0	~	n.d.	~	n.d.	~
100 ppm C2H4	n.d.	~	104.8	~	n.d.	~
100 ppm C2H6	n.d.	~	n.d.	~	97.4	~
HP. Helium Blank	~	n.d.	~	n.d.	~	n.d.
H2O Blank	~	n.d.	~	n.d.	~	n.d.
MW-62 (5-6)	~	n.d.	~	n.d.	~	n.d.
MW-64 (5-4)	~	n.d.	~	n.d.	~	n.d.
MW-147 (5-5)	~	n.d.	~	n.d.	~	n.d.
196-A (5-4)	~	n.d.	~	n.d.	~	n.d.
196-B (5-4)	~	n.d.	~	n.d.	~	n.d.
196-B Lab Dup	~	n.d.	~	n.d.	~	n.d.
MW-197	~	n.d.	~	n.d.	~	n.d.
MW-198 (5-4)	~	0.000	~	n.d.	~	n.d.
MW-199D	~	0.001	~	n.d.	~	n.d.
MW-199M	~	0.001	~	n.d.	~	n.d.
MW-199S	~	0.001	~	n.d.	~	n.d.
MW-199S F Dup	~	n.d.	~	n.d.	~	n.d.
MW-201 (5-4)	~	n.d.	~	n.d.	~	n.d.
MW-203 (5-5)	~	n.d.	~	n.d.	~	n.d.
MW-206 (5-5)	~	0.000	~	n.d.	~	n.d.
MW-207 (5-5)	~	n.d.	~	n.d.	~	n.d.
MW-208 (5-5)	~	n.d.	~	n.d.	~	n.d.
MW-208 L Dup	~	n.d.	~	n.d.	~	n.d.
[illegible]-209 (5-5)	~	n.d.	~	n.d.	~	n.d.
[illegible]209D (5-5)	~	0.001	~	n.d.	~	n.d.
[illegible]209M (5-5)	~	n.d.	~	n.d.	~	n.d.
[illegible]210 (5-5)	~	0.001	~	n.d.	~	n.d.
MW-210D (5-5)	~	n.d.	~	n.d.	~	n.d.
MW-210D F Dup	~	0.000	~	n.d.	~	n.d.
MW-210M (5-5)	~	n.d.	~	n.d.	~	n.d.
MW-211 (5-4)	~	n.d.	~	n.d.	~	n.d.
MW-232	~	n.d.	~	n.d.	~	n.d.
MW-233 (5-4)	~	n.d.	~	n.d.	~	n.d.
MW-236	~	n.d.	~	n.d.	~	n.d.
MW-236 L Dup	~	n.d.	~	n.d.	~	n.d.
MW-237 (5-4)	~	0.002	~	n.d.	~	n.d.
MW-238 (5-4)	~	n.d.	~	n.d.	~	n.d.
PES-1S (5-6)	~	0.000	~	n.d.	~	n.d.
PES-2D (5-6)	~	n.d.	~	n.d.	~	n.d.
PES-3D (5-6)	~	0.003	~	0.001	~	n.d.
PES-3D F Dup	~	0.002	~	0.000	~	n.d.
PES-4D (5-5)	~	0.001	~	n.d.	~	n.d.
PES-5D (5-6)	~	0.001	~	n.d.	~	n.d.
PES-6D (5-6)	~	n.d.	~	n.d.	~	n.d.
PSE-6S (5-5)	~	n.d.	~	n.d.	~	n.d.
10ppm CH4	10.8	~	n.d.	~	n.d.	~
10ppm C2H4	n.d.	~	11.0	~	n.d.	~
10ppm C2H6	n.d.	~	n.d.	~	11.2	~
Lower Limit of Quantitation	10.0	0.001	10.0	0.003	10.0	0.002

[illegible]its for the samples are mg/L dissolved in water.

[illegible]or the standards are parts per million.

[illegible]tes not applicable

nd denotes not detected

ROBERT S. KERR
ENVIRONMENTAL
RESEARCH LABORATORY
ADA, OKLAHOMA

COPY 35

UNITED STATES
ENVIRONMENTAL PROTECTION AGENCY

SOURCE Warren AFB DATE 5/3/99

ANALYSIS Water Quality GROUP all mg/L ANALYST PJ2

SAMPLE	TIME	Fe^{++}	Alk	CO_2	$S^=$			
MW-197	11:15	<.1	220	25	<.1			
MW-232	13:10	<.1	220	25	<.1			
MW-199S	14:05	<.1	200	10	<.1			
MW-199M	14 55	<.1	140	10	<.1			
MW-199D	15:45	<.1	120	10	<.1			
	5/4/99							
MW-196A	0815	<.1	140	15	<.1			
196 = MW-196B	0930	<.1	120	15	<.1			
MW-64	0945	<.1	200	20	<.1			
MW-233	1035	<.1	140	15	<.1			
MW-201	1340	<.1	280	25	<.1			
MW-238	1420	<.1	300	25	<.1	pH = 7.32		
MW-239	1440	<.1	220	25	<.1			
MW-237	1530	<.1	240	20	<.1			
MW-198	1630	<.1	220	15	<.1			
5-5-99 → MW-211	1645	<.1	200	25				
5-5-99 MW PES WS	9:24	<.1	160	30	<.1			

REMARKS

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UNITED STATES
ENVIRONMENTAL PROTECTION AGENCY

SOURCE Warren AFB, WY DATE 5-5-99

ANALYSIS Water Quality GROUP _____ ANALYST MB

SAMPLE	TIME	Fe^{+2}	ALK	CO_2	$S^{=}$			
MW-210M	1044	<.1	120	25	<.1			
MW-210	1054	<.1	180	25	<.1			
MW-210D	1126	<.1	120	20	<.1			
MW-147	1207	<.1	200	35	<.1	pH=7.21		
PES-4D	1335	<.1	160	15	<1			
MW-209M	1435	<.1	200	25	<.1			
MW-209	1510	<.1	240	30	<.1			
MW-209D	1533	<.1	180	30	<.1			
MW-207	1605	<.1	200	40	<.1			
MW-203	1700	<.1	200	40	<.1	pH=7.33		
MW-208	1742	<.1	240	35	<.1			
MW 206	1830	<.1	180	20	<.1	pH=6.96		

REMARKS

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UNITED STATES
ENVIRONMENTAL PROTECTION AGENCY

SOURCE Warren AFB DATE 5/6/91

ANALYSIS Water Quality GROUP Nat. atten ANALYST

SAMPLE	TIME	Fe^{+2}	ALK	CO_2	$S^{=}$			
MW-62	830	<.1	160	35	<.1			
PES-2D	936	<.1	240	35	<.1			
PES-1S	1020	<.1	220	40	<.1			
PES-3D	1049	<.1	140	40	<.1	pH = 7.09		
PES-6D	1105	<.1	120	30	<.1	pH = 7.18		
PES-5D	1149	<.1	140	40	<.1			

REMARKS

APPENDIX D

COST CALCULATIONS

PARSONS Calculation Page				Job Number 722450.30050	Page 1 of 1
Rev	Date 8/18/99	By BMH	Ck	Subject: Cost Calculations for Alternative 2 RNA, LTM, Soil Gas Source Identification/ Characterization, and Source Removal LF-03, F.E. Warren AFB	

Capital Costs

Source Area Identification/ Characterization

Soil Gas Survey for Source Characterization

- 20 ft node centered grid for an area of 25,600ft^2 = 240 sampling points.

Geoprobe Rental (8 pts. Per day)	31 days x	$1,000	/day	$31,000
Soil Gas Analysis (EPA TO-3)	240 samples x	$130	/sample	$31,200
Sampling Labor	496 hours x	$60	/hour	$29,760
Sample Shipping		$500	lump sum	$500
Per Diem	62 days x	$88	/day	$5,456
Travel		$200	lump sum	$200
Equipment Rental (Meters)		$2,000	lump sum	$2,000
Progress Report	40 hours x	$70	/hour	$2,800
Contingency (10%)				$7,192
			Subtotal for Soil Gas Investigation:	$79,108

Source Area Removal

Excavation

Total Area of Site:	15,000	ft^2
	1,666.7	yd^2
Total Volume of Soil to be Excavated (to an assumed 15 ft bgs):	225,000	ft^3
	8,325	yd^3
Total Weight of Soil to be Excavated (Weight of soil = 1.25 tons/yd^3):	10,406.3	tons
Total Volume of Soil to be Disposed of (Assume Contaminant thickness of 15 ft):	8,325	yd^3
Total Weight of Soil to be Disposed of:	10,406.3	tons

ITEM (With Costing Reference)	# Units	Unit	Unit Cost[a/]	Total
Soil Excavation (RSMeans 17 03 0278)	8,325.0	yd^3	$1.45 /yd^3	$12,071.25
Waste Soil Transport (RSMeans 33 19 0205)	8,325.0	20 yd^3/mile[a]	$3.44 /20 yd^3/mil	$28,638.00
Waste Disposal at Landfill (Denver Arapahoe Disposal)	8,325.0	yd^3	$15.00 /yd^3	$124,875.00
Site Resotration	15,000.0	yd^2	$2.00 /yd^3	$30,000.00
Engineering Oversight	120	HR	$60.00 /Hour	$7,200.00
			Subtotal for Soil Excavation:	$202,784.25

Summary of Capital Costs

Soil Gas Survey for Source Characterization:	$79,108
Soil Excavation:	$202,784
Total Capital Costs =	$281,892
LTM Plan (from Alternative 1) **Total Cost of LTM Program =**	$1,609,287
Total Cost Estimate of Alternative 2 =	**$1,891,179**

PARSONS Calculation Page					Job Number 722450.30050	Page 1 of 2
Rev	Date 8/18/99	By BMH	Ck	Subject:	Cost Calculations for Alternative 1 RNA + LTM LF-03, F.E. Warren AFB	

Groundwater Sampling - Years 2000 - 2029
Cost per Event

31 Long-Term Monitoring Wells
2 Surface-Water Stations
10 QA/QC (3 dupl, 1 field blank, 2 trip blank, 2 MS, 2 MSD)
43 Total Samples

Sampling Labor	160	hours x	$60	/hour	$9,600
Analytical Subcontractor					
43 VOCs[a/]			$160	/each	$6,880
43 Methane/Ethane/Ethene			$101	/each	$4,343
43 Nitrate/Nitrite			$20	/each	$860
33 Field Parameters			$20	/each	$660
Supplies			$500	lump sum	$500
Travel			$800	lump sum	$800
Per Diem	20	days x	$88	/day	$1,760
Data Management	40	hours x	$60	/hr	$2,400
Data Validation	24	hours x	$60	/hr	$1,440
Reporting/Project Management Labor					
Word Processing	10	hours x	$25	/hour	$250
CADD	15	hours x	$50	/hour	$750
Reproduction	8	hours x	$20	/hour	$160
Staff Level	50	hours x	$60	/hour	$3,000
Proj. Manager	20	hours x	$80	/hour	$1,600
Editor	6	hours x	$60	/hour	$360
Reporting/Project Management ODCs			$400	lump sum	$400
				Total for 1 Sampling Event	$35,763

[a/] VOC analysis includes BTEX, CAHs, and MTBE.

PARSONS Calculation Page					Job Number 722450.30050	Page 2 of 2
Rev	Date 8/19/99	By BMH	Ck	Subject:	Cost Calculations for Alternative 1 RNA + LTM LF-03, F.E. Warren AFB	

Summary of Total Cost

Monitoring Costs

Annual Monitoring of 31 wells and 2 surface water stations, 2000-2003 (4 events)

Cost per Event	2000	$35,763	
i=4%, n=1	2001	$37,253.13	
i=4%, n=2	2002	$38,805.34	
i=4%, n=3	2003	$40,422.23	
i=4%, n=4	2004	$42,106.49	
		Total Cost	$194,350

Biennial Monitoring of 31 wells and 2 surface water stations, 2005-2029 (13 events)

i=4%, n=05	2005	$43,860.92	
i=4%, n=07	2007	$47,592.15	
i=4%, n=09	2009	$51,640.79	
i=4%, n=11	2011	$56,033.84	
i=4%, n=13	2013	$60,800.61	
i=4%, n=15	2015	$65,972.88	
i=4%, n=17	2017	$71,585.16	
i=4%, n=19	2019	$77,674.87	
i=4%, n=21	2021	$84,282.62	
i=4%, n=23	2023	$91,452.50	
i=4%, n=25	2025	$99,232.31	
i=4%, n=27	2027	$107,673.95	
i=4%, n=29	2029	$116,833.71	
		Total Cost	$974,636

Site Management every year (35 years)

Annual Cost	$4,000		
i=4% n=30	Cost Factor =	110.0752076	
		Total Cost	$440,301

Total Costs of LTM Program	**$1,609,287**

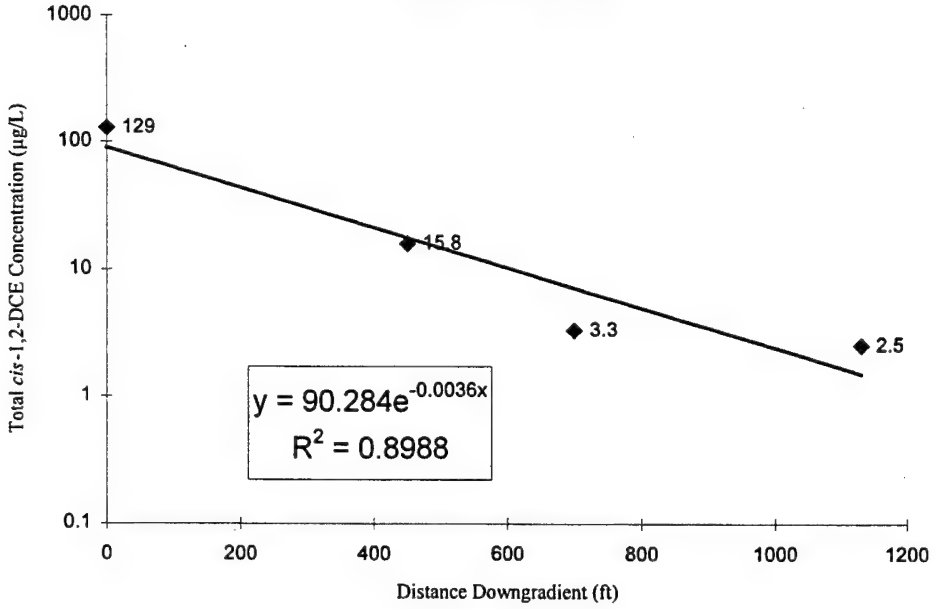
APPENDIX E

SUPPORTING MODEL INPUT AND CALCULATIONS FOR GROUNDWATER/FATE AND TRANSPORT MODELING

FIRST-ORDER DECAY RATE CALCULATION
USING THE METHOD OF BUSCHECK AND ALCANTAR (1995)
SITE LF-03 RNA TS
F.E. WARREN AFB, WYOMING

Point	Distance (ft) Downgradient	*cis*-1,2-DCE (µg/L) May-99
209	0	129
210	450	15.8
211	700	3.3
PES-6S	1130	2.5
199	1520	0.0

PLOT OF *cis*-1,2-DCE CONCENTRATION VERSUS DISTANCE

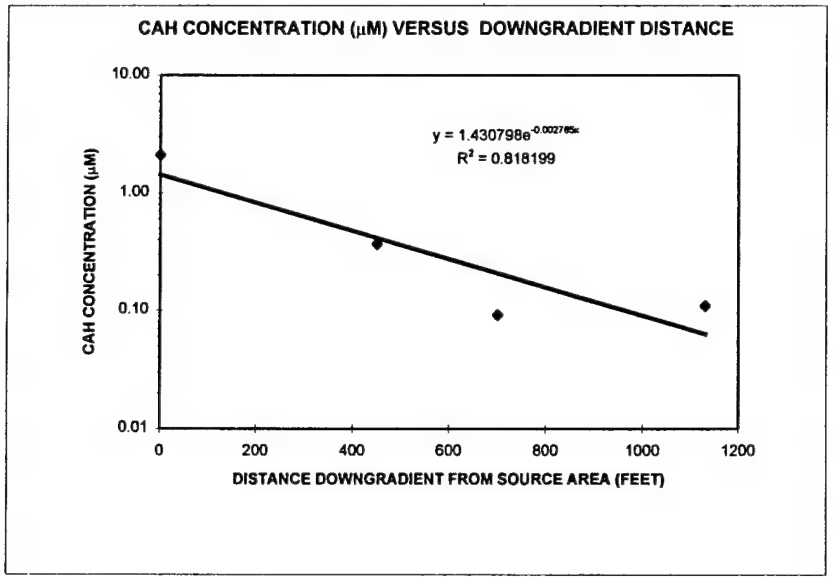


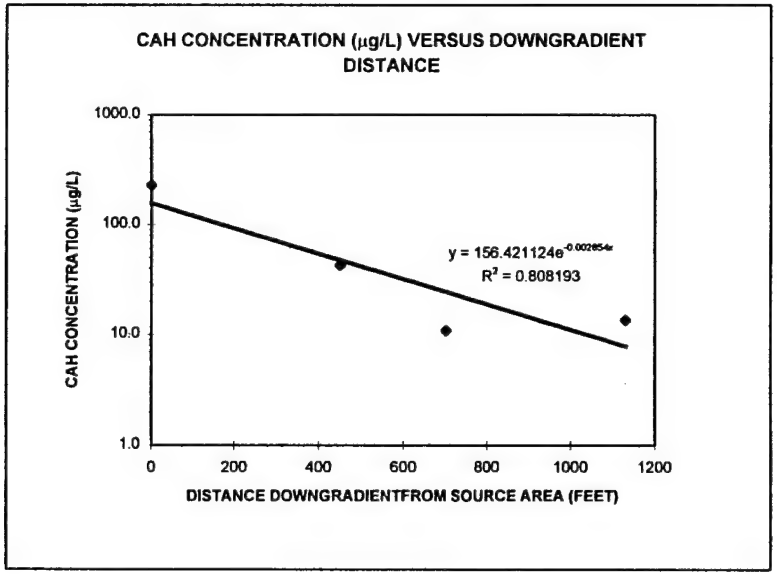
$$\lambda = v_c/4\alpha_x([1+2\alpha_x(k/v_x)]^2-1)$$

where	v_c =	0.024	ft/day
	α_x =	53.1	feet
	k/v =	0.0036	
therefore	λ =	1.03E-04	$days^{-1}$
	half life =	18.45	years

ESTIMATED FIRST-ORDER RATE CONSTANT CALCULATION FOR TOTAL CHLORINATED ETHENES
USING THE METHOD OF BUSCHECK AND ALCANTAR (1995)
MAY 1999
SITE LF-03 RNA TS
F.E. WARREN AFB, WYOMING

Well	Distance Downgradient	PCE (µg/L) May-99	PCE (µM) May-99	TCE (µg/L) May-99	TCE (µM) May-99	Total DCE (µg/L) May-99	Total DCE (µM) May-99	VC (µg/L) May-99	VC (µM) May-99	Total CAH (µg/L) May-99	Total CAH (µM) May-99
209	0	0.0	0.00	93.1	0.7	134.7	1.4	0.0	0.0	227.8	2.1
210	450	0.0	0.00	26.7	0.2	15.8	0.2	0.0	0.0	42.5	0.4
211	700	0.0	0.00	7.5	0.1	3.3	0.0	0.0	0.0	10.8	0.1
PES-6S	1130	0.0	0.00	11.0	0.1	2.5	0.0	0.0	0.0	13.5	0.1
199	1520	0.0	0.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0





Method of Buscheck & Alcantar (1995)

$$\lambda = v_c/4\alpha_x([1+2\alpha_x(k/v_x)]^2-1)$$

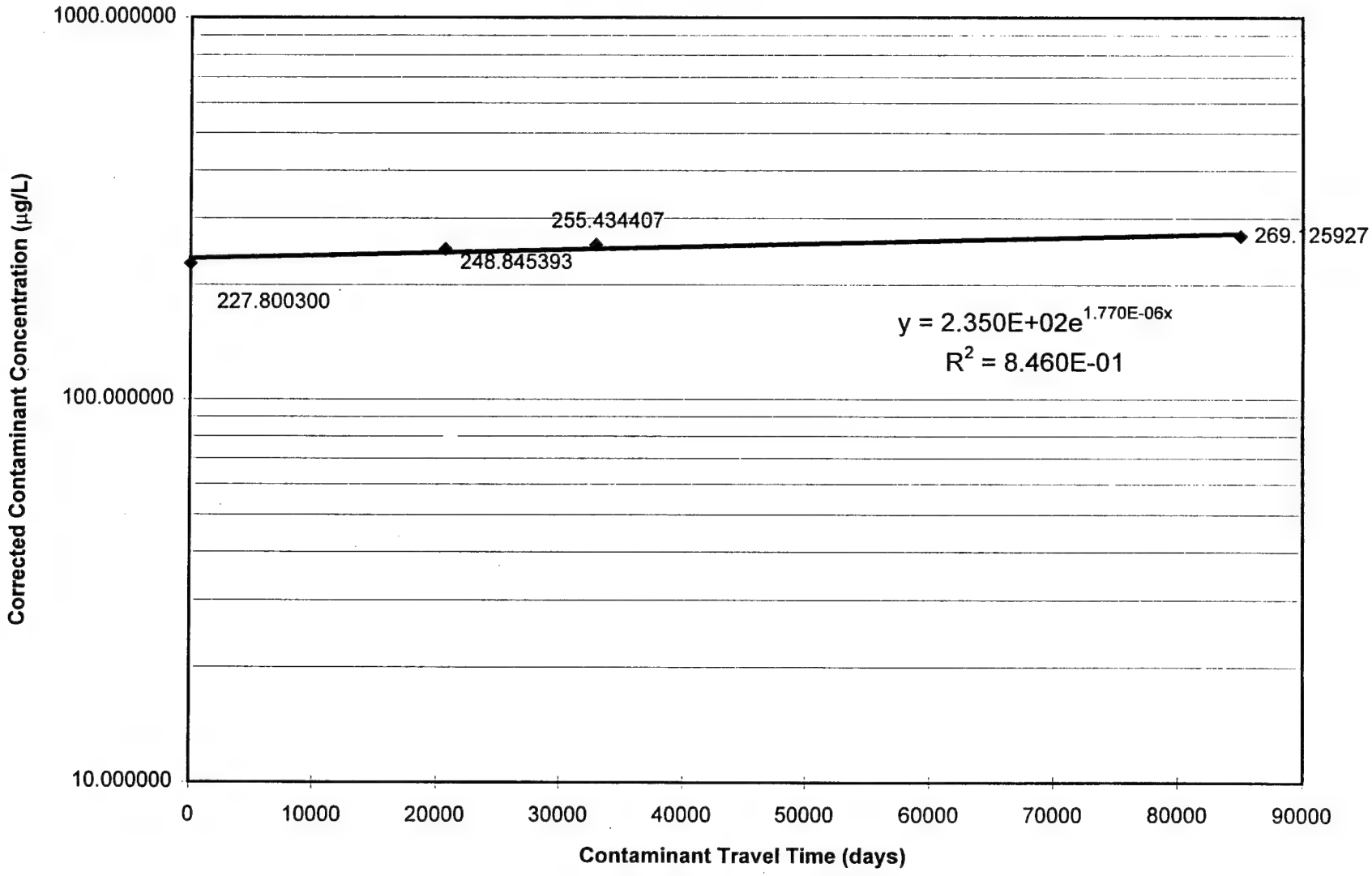
where	v_c =	0.023	ft/day
	α_x =	53.1	ft
	k/v =	0.0028	
therefore	λ =	7.2962E-05	1/day
	λ =	7.2962E-03	%/day
	half life =	26.03	years

Method of Buscheck & Alcantar (1995)

$$\lambda = v_c/4\alpha_x([1+2\alpha_x(k/v_x)]^2-1)$$

where	v_c =	0.023	ft/day
	α_x =	53.1	ft
	k/v =	0.002654	
therefore	λ =	6.9644E-05	1/day
	λ =	6.9644E-03	%/day
	half life =	27.27	years

REDUCTIVE DECHLORINATION RATE FOR CHLORINATED ETHENES
209 > 210 > 211 > PES-6S
MAY 1999
SITE LF-03 RNA TS
F.E. WARREN AFB, WYOMING



REDUCTIVE DECHLORINATION RATE FOR CHLORINATED ETHENES
209 > 210 > 211 > PES-6S
MAY 1999
SITE LF-03 RNA TS
F.E. WARREN AFB, WYOMING

The following procedures outlined by Moutoux et al. (1996)

Step 1: Enter Observed Contaminant Concentration (mg/L)

Well	PCE	TCE	DCE	VC	Ethene	Total CAHs
209	0.0	93.1	134.7	0.0	0	227.8
210	0.0	26.7	15.8	0.0	0	42.5
211	0.0	7.5	3.3	0.0	0	10.8
PES-6S	0.0	11.0	2.5	0.0	0	13.5

Step 2: Compute Molar Concentrations (micromoles/Liter)

Well	M_{PCE}	M_{TCE}	M_{DCE}	M_{VC}	M_{Ethene}	Total M_{CAHs}
209	0.00	0.71	1.39	0.00	0.00	2.10
210	0.00	0.20	0.16	0.00	0.00	0.37
211	0.00	0.06	0.03	0.00	0.00	0.09
PES-6S	0.00	0.08	0.03	0.00	0.00	0.11

Step 3: Compute Carbon Equivalents

Well	Total M_{CAHs}	x 2	= Ceqi
209	2.10		4.20
210	0.37		0.73
211	0.09		0.18
PES-6S	0.11		0.22

Step 4: Compute Chlorine Equivalents

Well	M_{PCE} x 4	M_{TCE} x 3	M_{DCE} x 2	M_{VC}	S = $Cleq_i$
209	0.00	2.13	2.78	0.00	4.90
210	0.00	0.61	0.33	0.00	0.94
211	0.00	0.17	0.07	0.00	0.24
PES-6S	0.00	0.25	0.05	0.00	0.30

Step 5: Compute Corrected CAH Concentrations

$$C_{i,corr} = C_{i-1,corr} \times (Cleq_i / Cleq_{i-1}) \times (Ceq_{i-1} / Ceq_i)$$

Well	$C_{i-1,corr}$	$Cleq_i / Cleq_{i-1}$	Ceq_{i-1} / Ceq_i	$C_{i,corr}$
209	227.800300			227.800300
210	227.800300	0.190758	5.726534	248.845393
211	248.845393	0.255801	4.012794	255.434407
PES-6S	255.434407	1.264959	0.832913	269.125927

Step 6: Plot Exponential Trendline of Contaminant Concentration vs. Time

Well	Distance From Source (ft)	CAH avg. velocity (ft/day)*	CAH Travel Time (day)	$C_{i,corr}$
209	0	0.022	0	227.800300
210	455	0.022	20682	248.845393
211	715	0.022	32955	255.434407
PES-6S	1145	0.022	85000	269.125927

*Assumes an unretarded velocity of 0.026 feet/day and a retardation coefficient of 1.2.

Reductive Dechlorination Rate

$C = C_0 e^{-kt}$ where:

C = Corrected Contaminant Concentration (mg/L) at time t (days)

C_0 = Initial Contaminant Concentration (mg/L)

k = Reductive Dechlorination Rate ($days^{-1}$)

from plot: $y = 2.350E+02e^{1.770E-06x}$ $k = 1.770\ E\text{-}06\ days^{-1}$

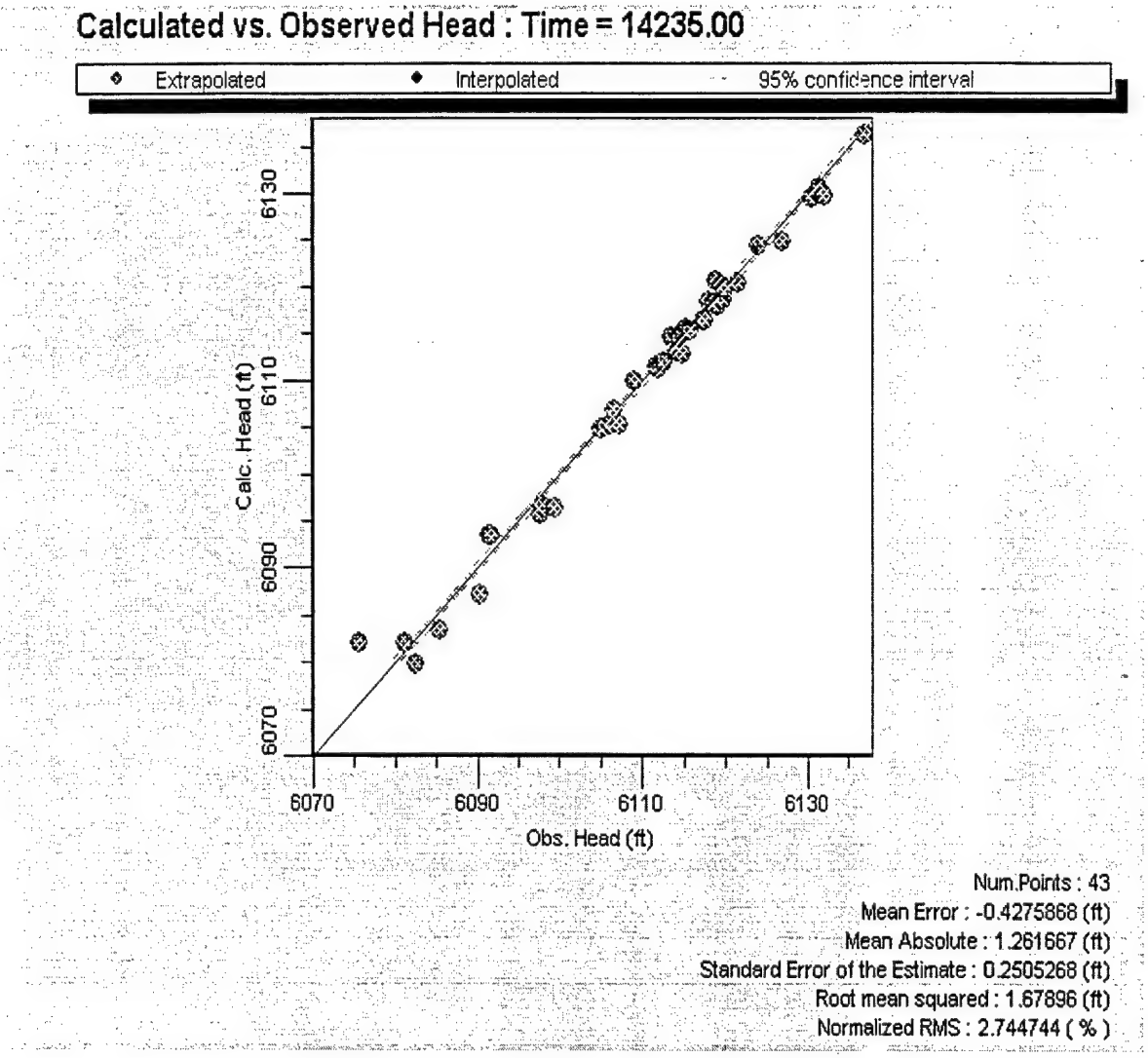
$k = 6.46\ E\text{-}04\ years^{-1}$

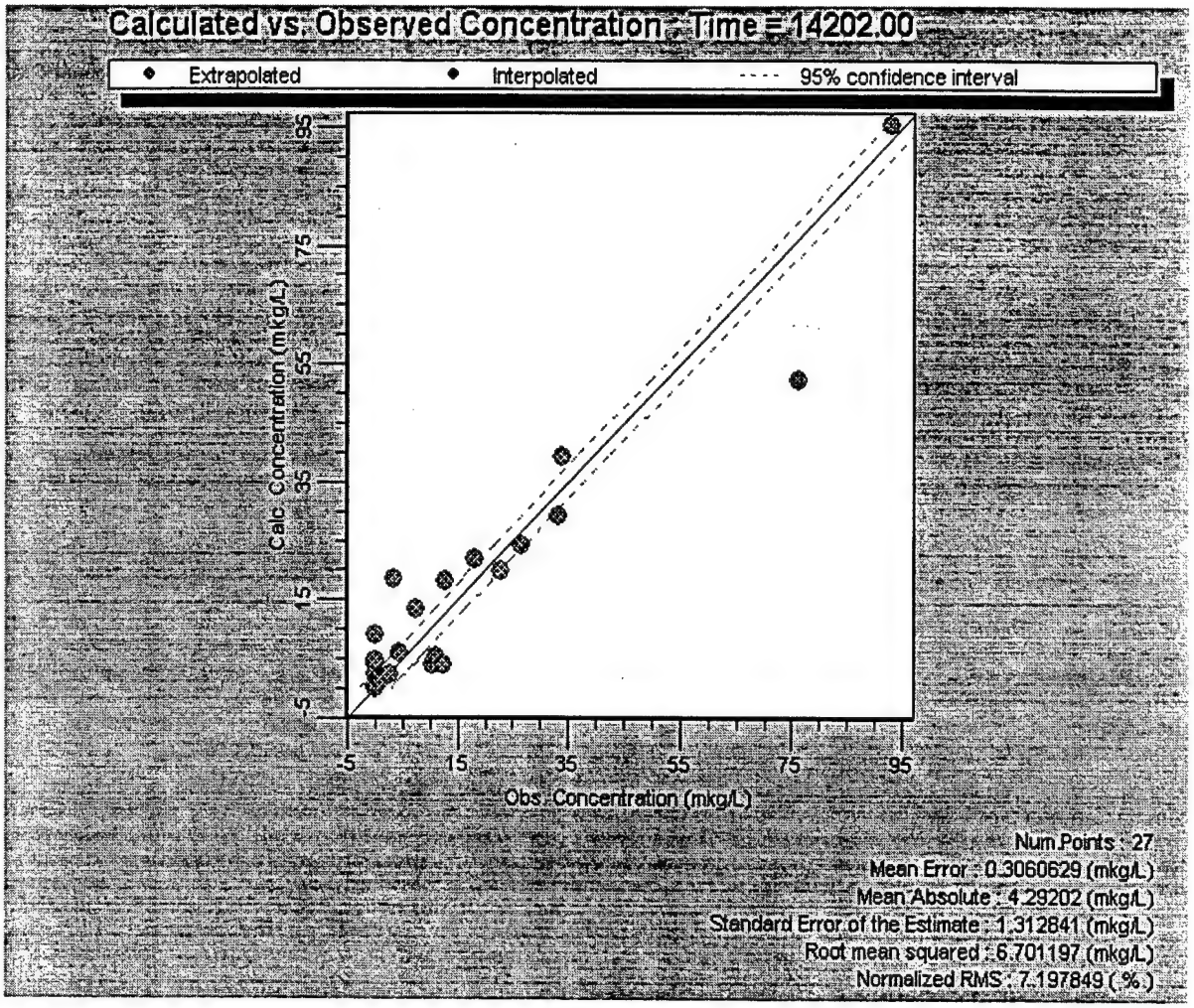
Time Period	Source Zone 1 78 Cells, 31200 ft^2		Source Zone 2 19 Cells, 7600 ft^2		Cumulative TCE Loaded (kg)
	TCE Flux per Cell (kg/yr)	Total TCE Flux (kg/yr)	TCE Flux per Cell (kg/yr)	Total TCE Flux (kg/yr)	
1999-2004	.000291	.02268	.003230	.06136	.4202
2004-09	.000199	.01550	.002210	.04199	.7076
2009-14	.000136	.01060	.001513	.02874	.9043
2014-19	.000093	.00725	.001035	.01967	1.0389
2019-24	.000064	.00497	.000708	.01346	1.1311
2024-29	.000044	.00340	.000485	.00921	1.1941
2029-34	.000030	.00233	.000332	.00630	1.2373
2034-39	.000020	.00159	.000227	.00431	1.2668
2039-44	.000014	.00109	.000155	.00295	1.2870
2044-49	.000010	.00075	.000106	.00202	1.3009

Table 6.? TCE Mass Loading History by Source Zone for Alternative 1, Monitored Natural Attenuation.

Time Period	Source Zone 1 78 Cells, 31200 ft²		Source Zone 2 19 Cells, 7600 ft²		Cumulative TCE Loaded (kg)
	TCE Flux per Cell (kg/yr)	Total TCE Flux (kg/yr)	TCE Flux per Cell (kg/yr)	Total TCE Flux (kg/yr)	
1999-2000	.000394	.03070	.002360	.04484	.0755
2000-01	.000365	.02846	.001180	.02242	.1264
2001-04	.000291	.02268	.000940	.01785	.2480
2004-09	.000199	.01550	.000643	.01222	.3866
2009-14	.000136	.01060	.000440	.00837	.4814
2014-19	.000093	.00725	.000302	.00573	.5463
2019-24	.000064	.00497	.000206	.00392	.5908
2024-29	.000044	.00340	.000141	.00268	.6212
2029-34	.000030	.00233	.000097	.00184	.6420
2034-39	.000020	.00159	.000066	.00126	.6563
2039-44	.000014	.00109	.000045	.00086	.6660
2044-49	.000010	.00075	.000031	.00059	.6727

Table 6.? TCE Mass Loading History by Source Zone for Alternative 2, Excavation of Source Zone 2.


Calculated vs. Observed Head : Time = 14235.00
Extrapolated
Interpolated
95% confidence interval
Calc. Head (ft)
6070
6090
6110
6130
Obs. Head (ft)
6070
6090
6110
6130
Num.Points : 43
Mean Error : -0.4275868 (ft)
Mean Absolute : 1.261667 (ft)
Standard Error of the Estimate : 0.2505268 (ft)
Root mean squared : 1.67896 (ft)
Normalized RMS : 2.744744 (%)


Calculated vs. Observed Concentration - Time = 14202.00
Extrapolated
Interpolated
95% confidence interval
Calc. Concentration (mkg/L)
Obs. Concentration (mkg/L)
-5
15
35
55
75
95
Num Points : 27
Mean Error : 0.3060629 (mkg/L)
Mean Absolute : 4.29202 (mkg/L)
Standard Error of the Estimate : 1.312841 (mkg/L)
Root mean squared : 6.701197 (mkg/L)
Normalized RMS : 7.197849 (%)

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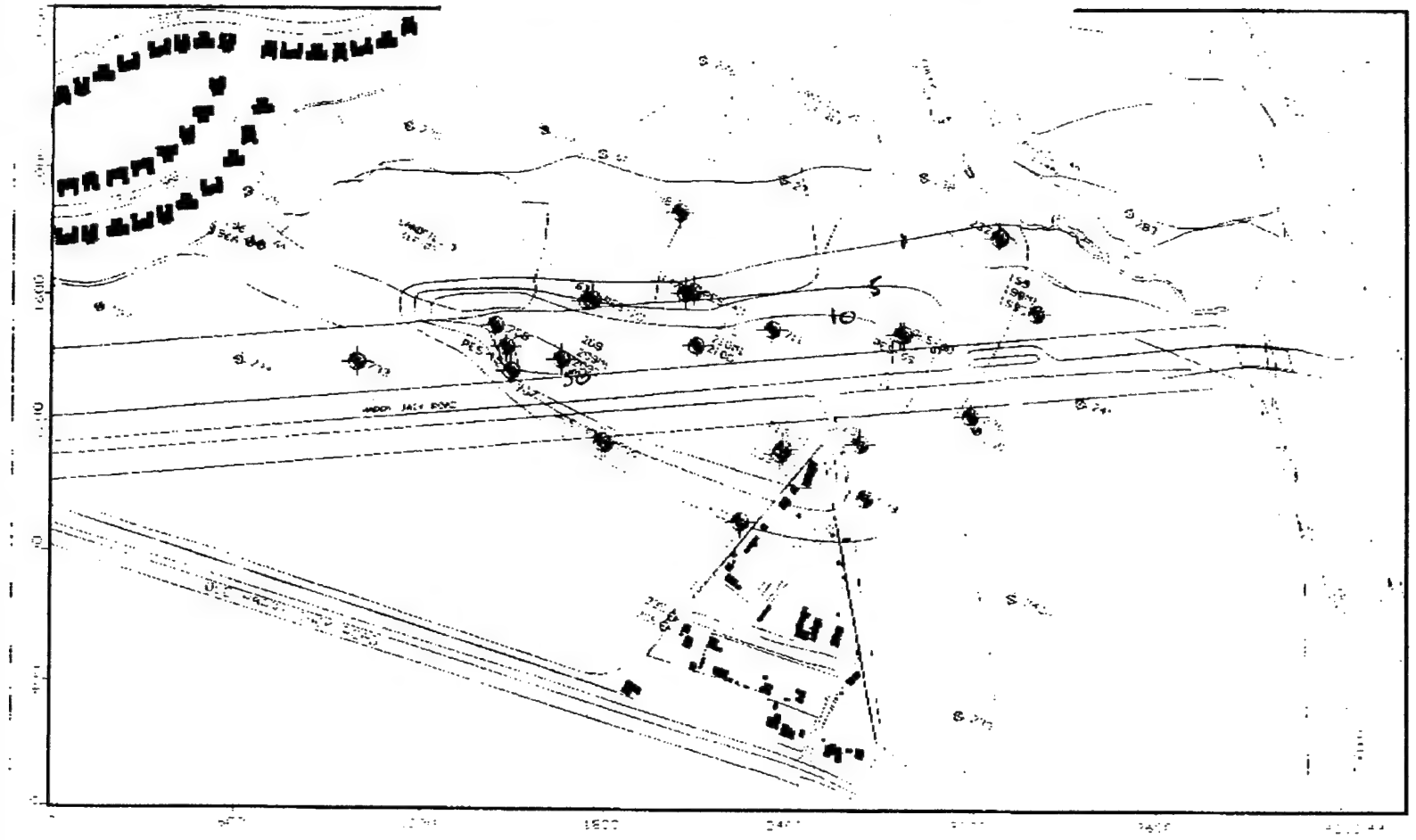

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ALT 1, 5 YR

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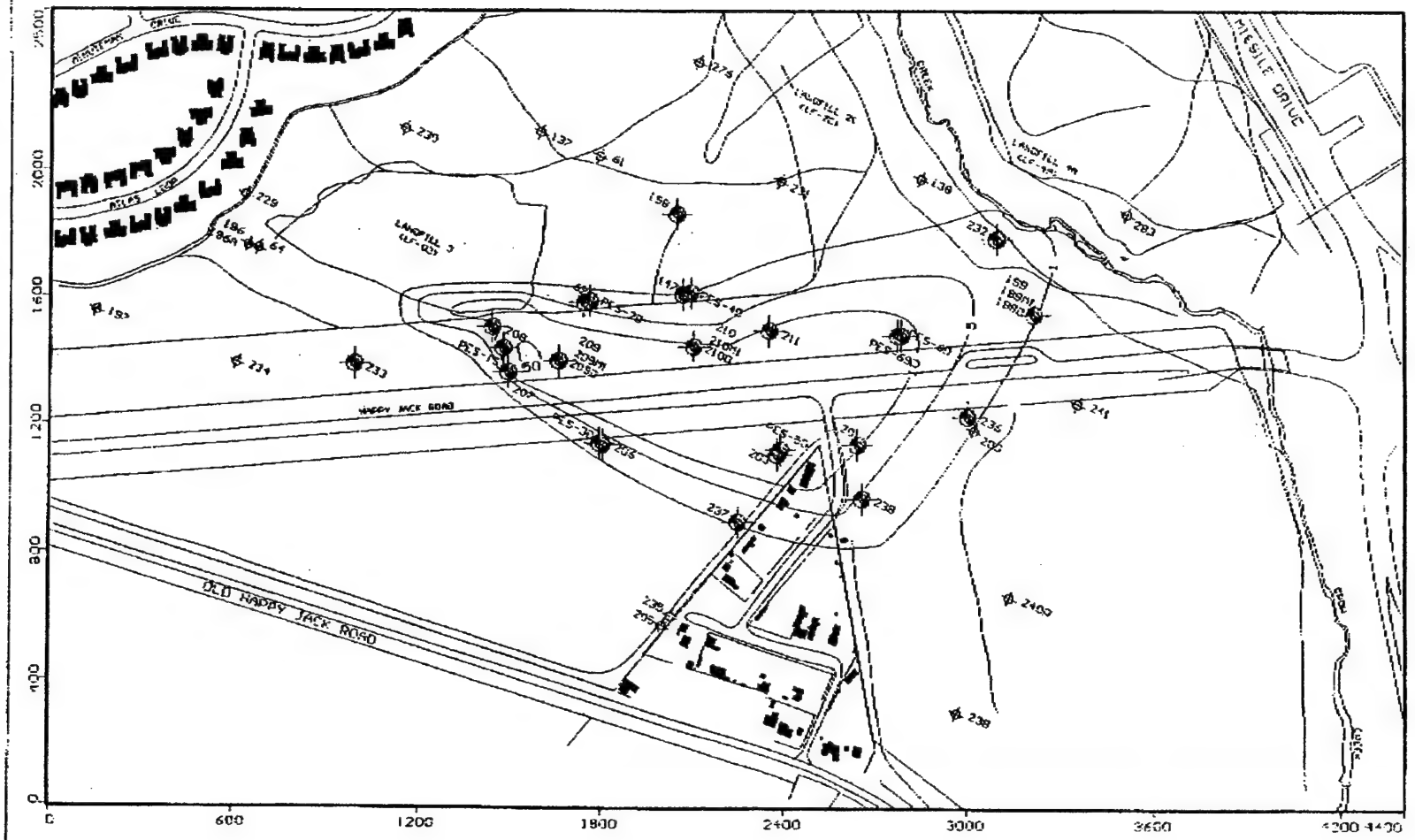

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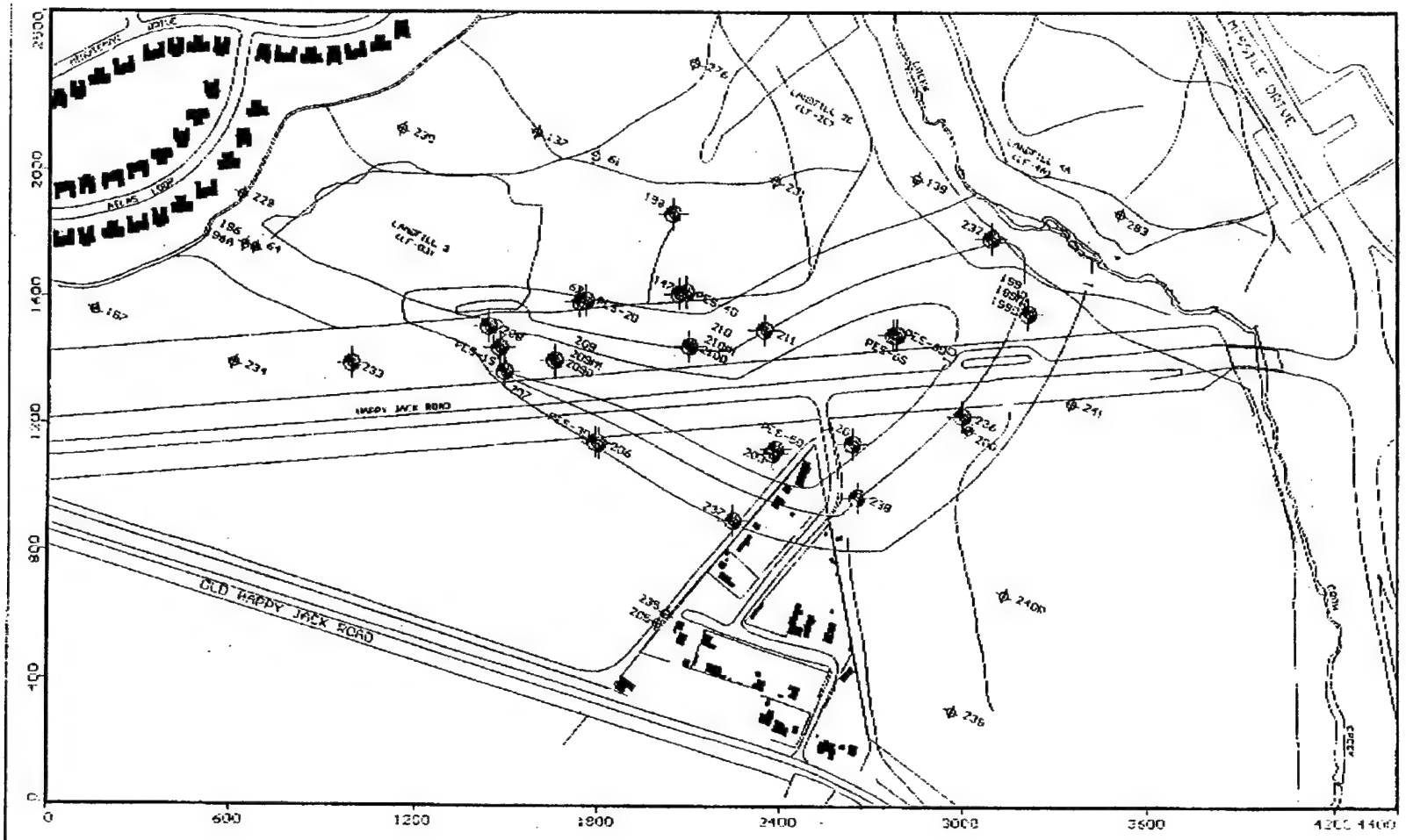

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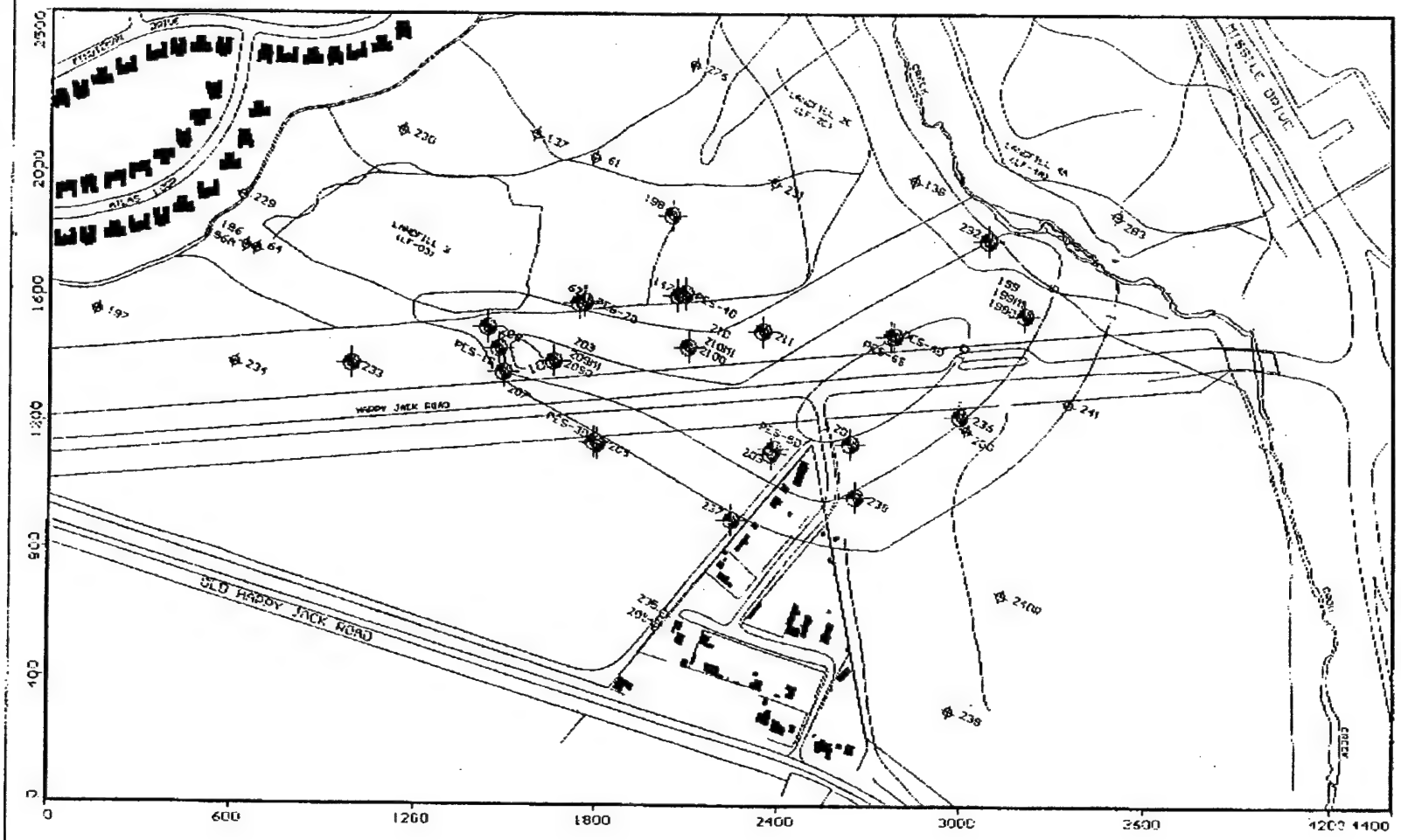

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ALT1, 30 YR

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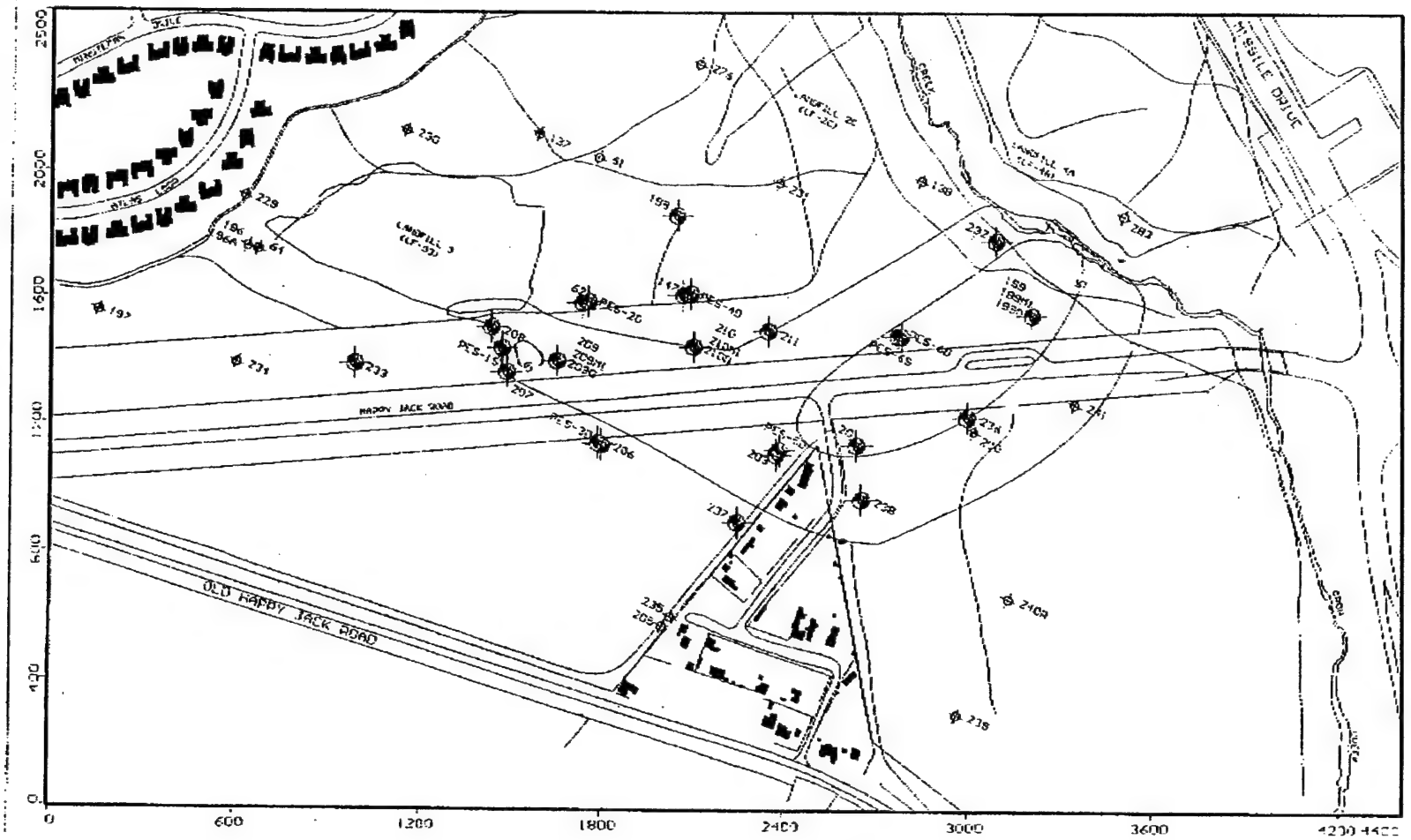

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ALT1, 39 YR

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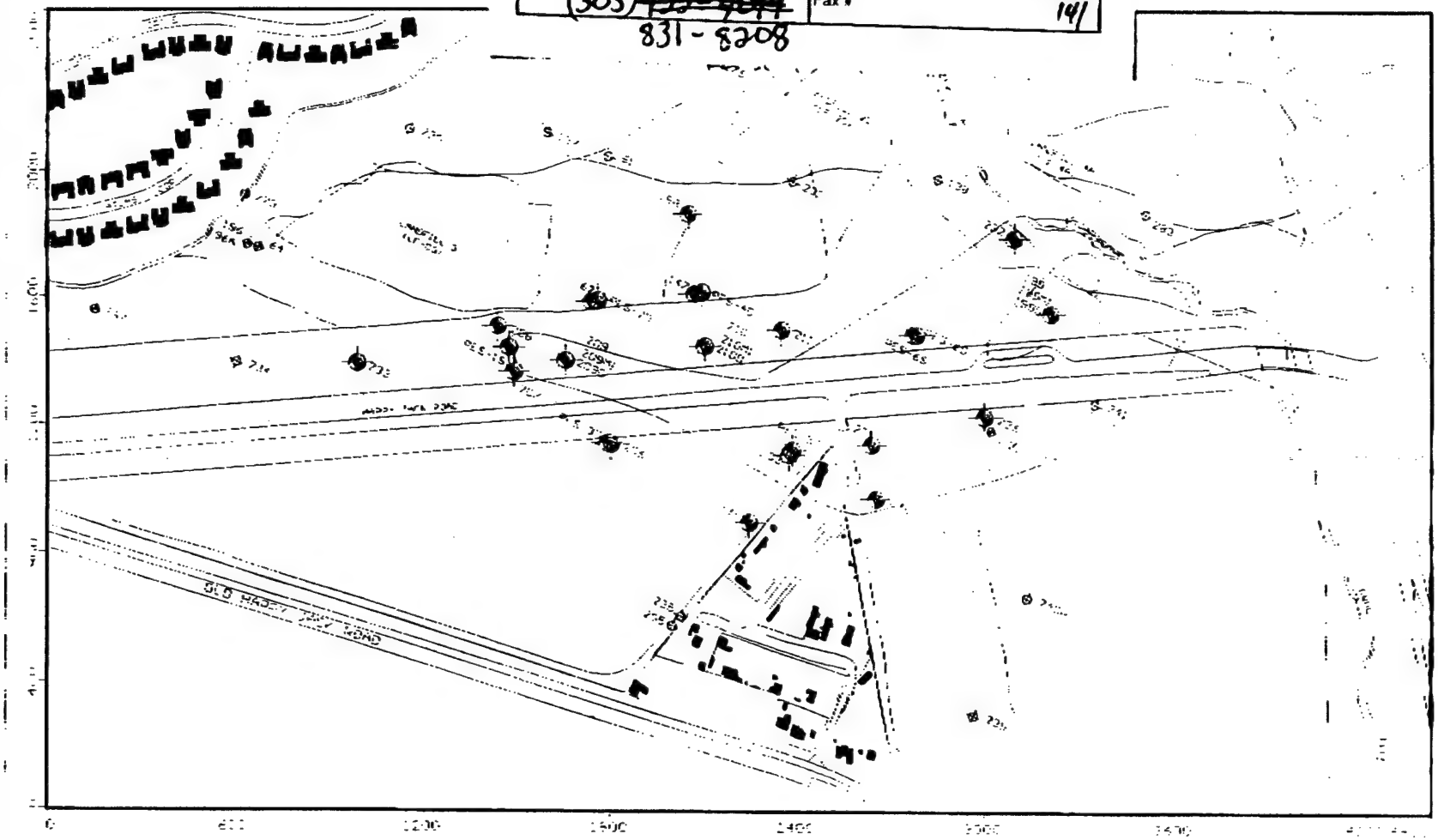
Phone #	Co.
Fax # (303) ~~[illegible]~~ 831-8208	Phone # (613) 554-4455 EXT 141



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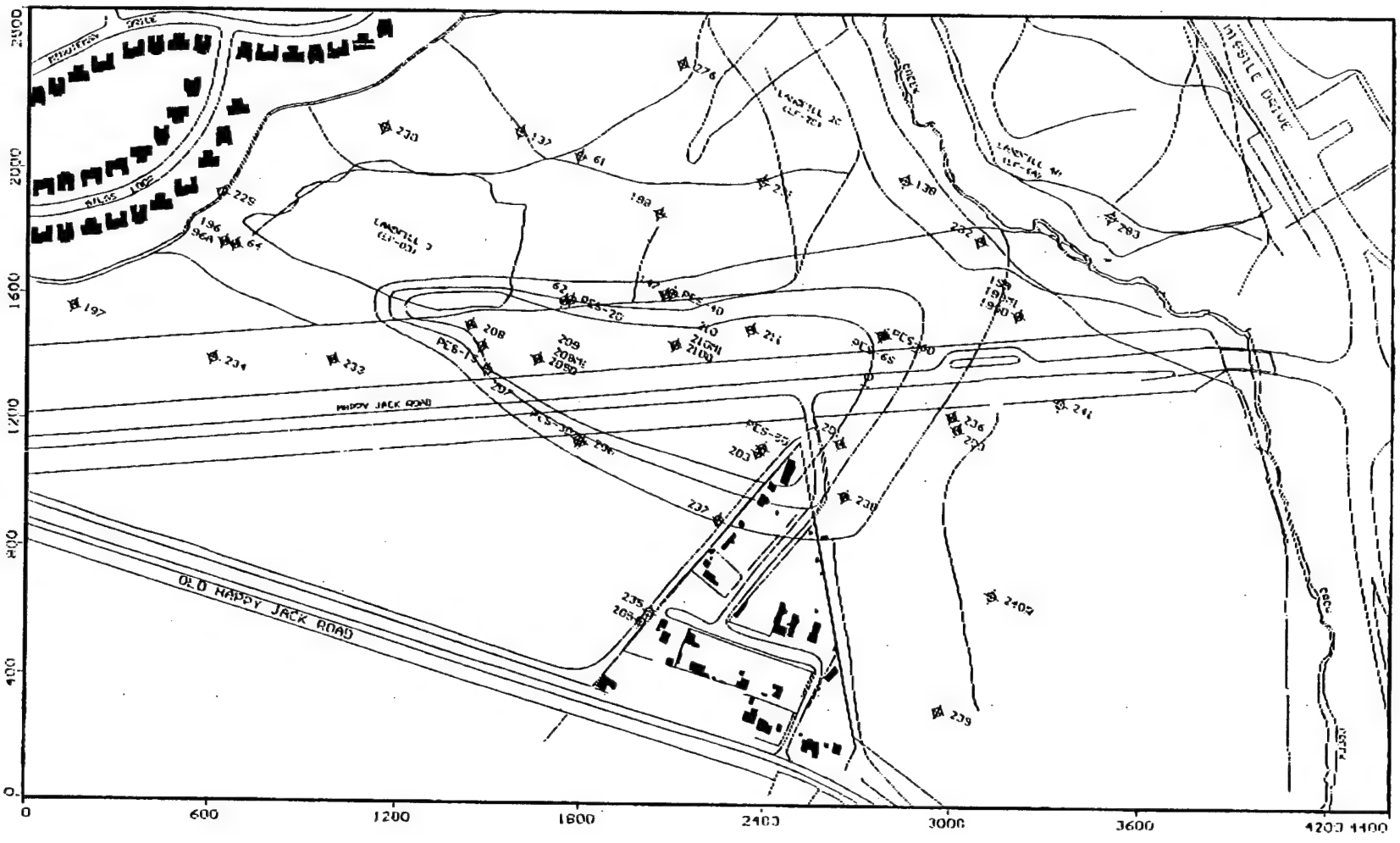

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ALT 2, 5YR

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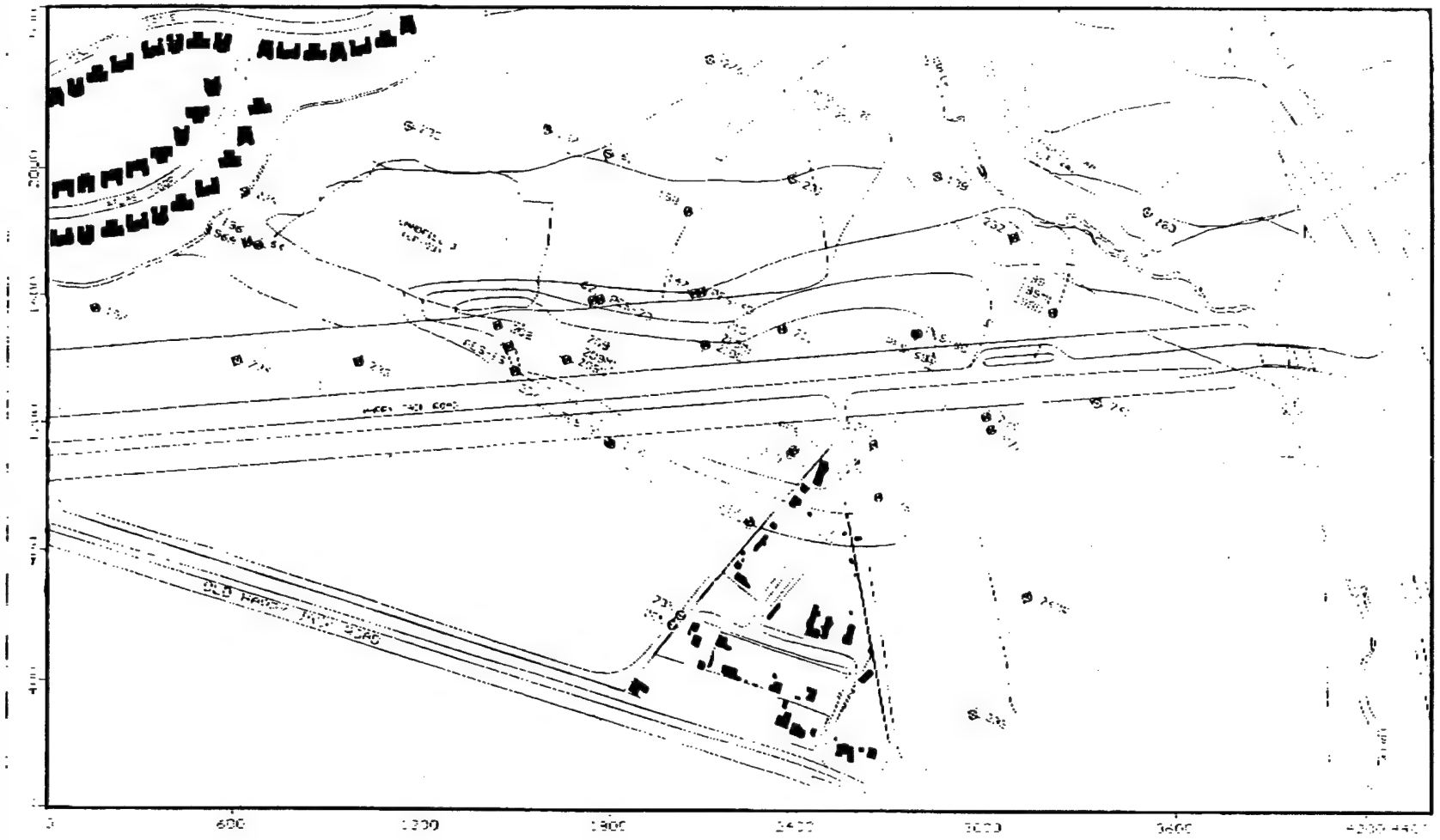

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ALT 2, 10 YR.

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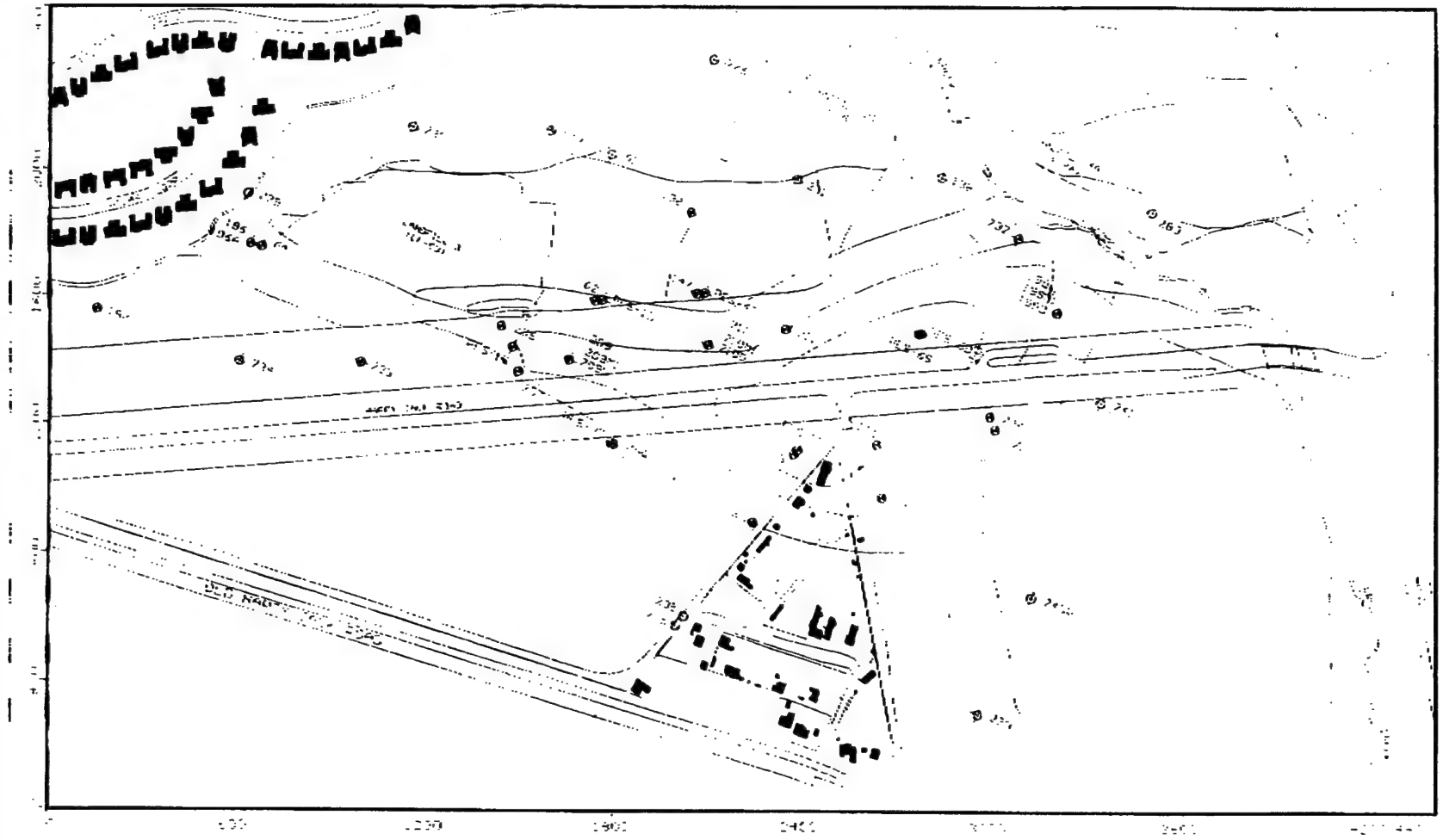

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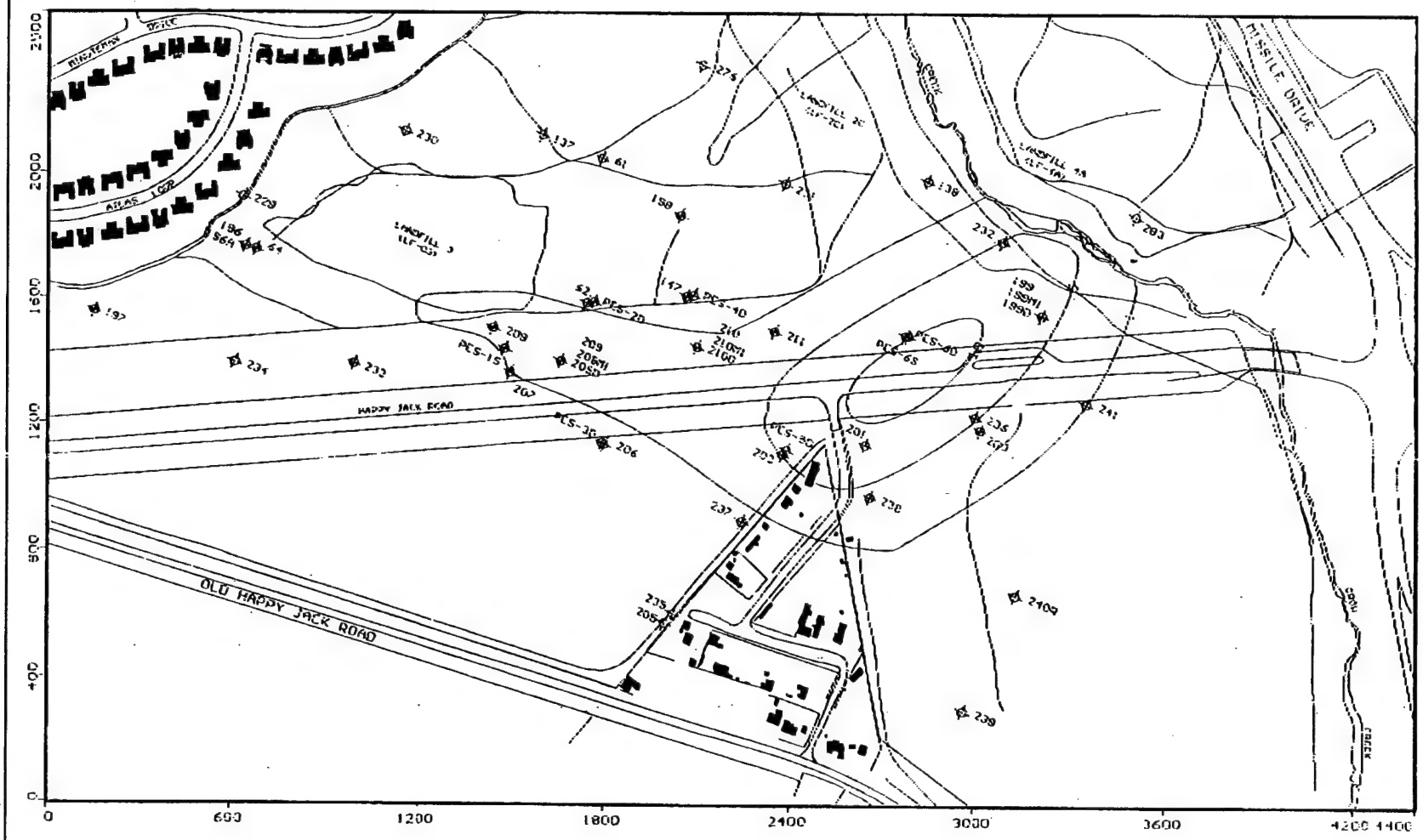

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ALT. 2, 30 YR

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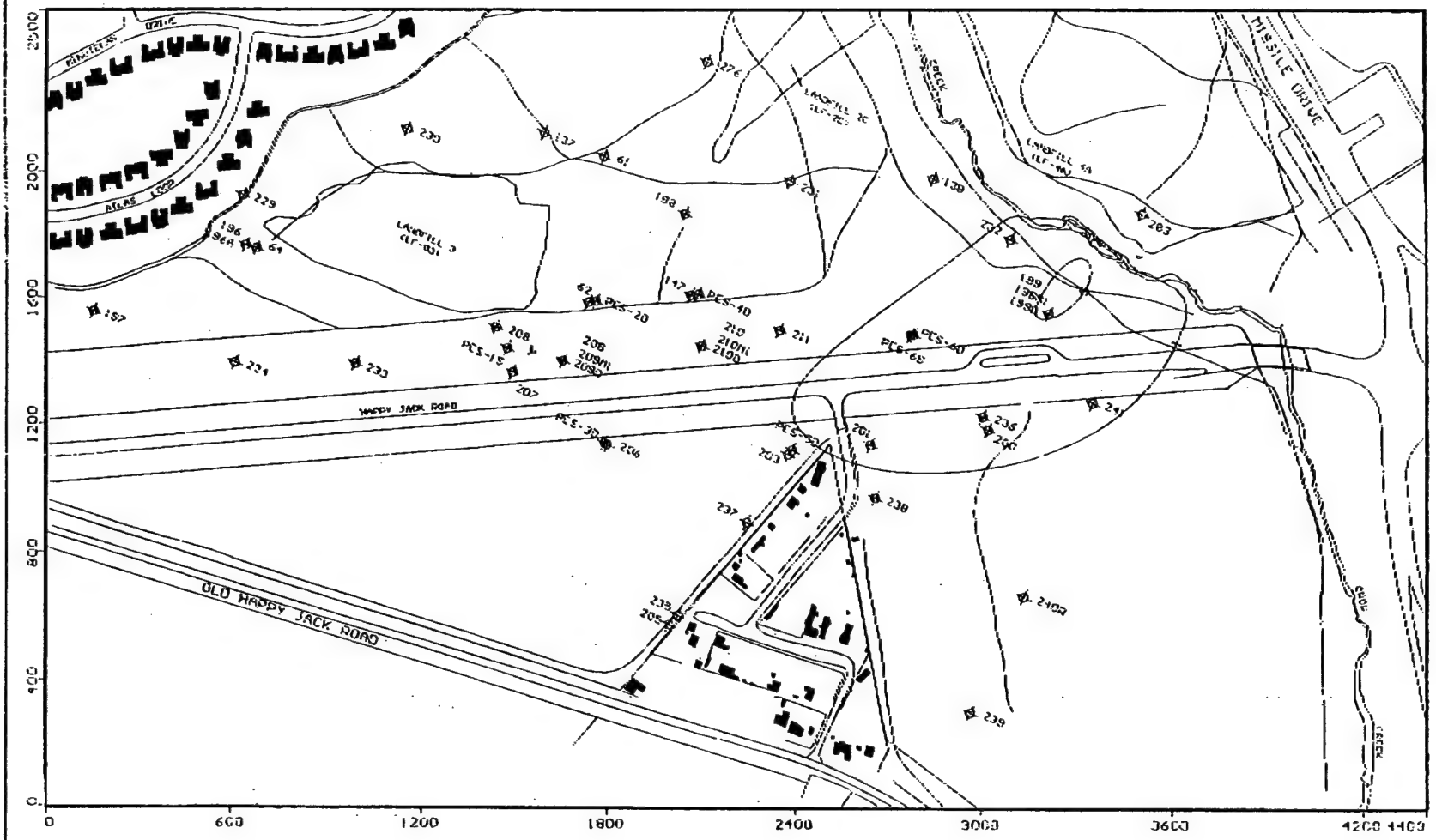

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ALT. 2, 50 YR

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APPENDIX F

MODEL INPUT AND OUTPUT FILES

APPENDIX G

COMMENTS AND RESPONSES

PARSONS

Parsons Engineering Science, Inc. • A Unit of Parsons Infrastructure & Technology Group Inc.
1700 Broadway, Suite 900 • Denver, Colorado 80290 • (303) 831-8100 • Fax: (303) 831-8208 • www.parsons.com

18 October 1999

Mr. Jerry Hansen
Technical Program Manager
AFCEE/ERT
3207 North Road, Bldg. 532
Brooks AFB, Texas 78235-5363
(210) 536-4353

Subject: Response to Comments on the Draft Treatability Study in Support of Monitored Natural Attenuation for Groundwater at Landfill 3 (Site LF-03), F.E. Warren AFB, Cheyenne, Wyoming (Contract F41624-92-D-8036-0006)

Dear Mr. Hansen:

This letter provides responses to comments received on the Draft Treatability Study (TS) in Support of Monitored Natural Attenuation (MNA) for Groundwater at Landfill 3 (Site LF-03), F.E. Warren Air Force Base (AFB), Cheyenne, Wyoming. The Draft MNA TS was prepared by Parsons Engineering Science, Inc. (Parsons ES) for the US Air Force Center for Environmental Excellence Technology Transfer Division (AFCEE/ERT) and F.E. Warren AFB. The intent of the report was to document the effectiveness of MNA at remediating groundwater contaminated by chlorinated solvents from past disposal activities at Landfill 3.

The draft MNA TS was submitted to AFCEE/ERT and F.E. Warren AFB on 23 August 1999. Comments on the draft report were received from AFCEE/ERT and F.E. Warren AFB dated 30 August 1999 (as reviewed by Jerry Hansen and Brady Baker), and dated 03 September 1999 (as reviewed by Jon Atkinson). An additional comment was provided by F.E. Warren AFB on 13 October 1999 to evaluate and model a total source reduction scenario. Responses to these comments were prepared by Parsons ES and are presented herein. The report also was reviewed without significant comment by Mr. Daniel Moore of the Wyoming Department of Environmental Quality (WDEQ) and Mr. Robert Stites of the US Environmental Protection Agency (USEPA, Region 8).

A. Responses to AFCEE/ERT Comments dated 30 August 1999:

Comment 1) Page ES-2, 2nd sentence "cis-1,2-DCE produced in the source area likely is aerobically biodegraded". Verify that this sentence is correct as other discussion indicates little degradation.

Parsons ES Response: *Degradation rates calculated by the method of Buscheck and Alcantar (Table 4.8) indicate that cis-1,2-DCE degrades at a rate of 0.0001 day^{-1} (half-life of 18 years) along a flowpath from well 209 to downgradient wells 210, 211, PES-6S, and 199. The source area is only slightly reducing with dissolved oxygen concentrations of approximately 1 milligram per liter (mg/L). If cis-1,2-DCE were degrading via anaerobic reductive dehalogenation, the daughter product vinyl chloride (VC) would be expected to be present (Section 4.1.2.1, Figure 4.1). However, if cis-1,2-DCE is being aerobically degraded, then VC would not be expected as a daughter product (Section 4.1.2, Figure 4.2). Therefore, a lack of VC supports the interpretation that the apparent degradation of cis-1,2-DCE is occurring aerobically.*

Further evidence of aerobic degradation of cis-1,2-DCE is discussed in Section 4.3.2, Presence of Daughter Products and CAH Ratios. Figure 4.10 indicates that the ratio of TCE to cis-1,2-DCE increases in the downgradient direction. Because the downgradient portion of the contaminant plume is aerobic and TCE is not known to degrade aerobically, the loss of cis-1,2-DCE relative to TCE supports aerobic degradation of cis-1,2-DCE.

Comment 2) Page 1-6, bottom of page, 15,400,00 cubic feet. Brady Baker indicates that this is at the high end as an estimate. Request that words be added to indicate that the actual number is suspected to be significantly lower.

Parsons ES Response: *The text will be changed for the reference to the landfill volume to: "The maximum volume of fill at LF-03 has been estimated to be 15,400,000 cubic feet (ft^3) (Engineering Science, Inc. [ES], 1985). However, the actual volume of fill at LF-03 is suspected to be significantly less."*

Comment 3) Page 1-9. 2nd paragraph, 5th sentence "hydrocarbons and also have" Check for missing words.

Parsons ES Response: *The sentence will be changed to "Fuel hydrocarbons and other chlorinated solvents also have been detected..."*

Comment 4) Page 2-3, table 2.2, indicate the datum used for the survey data.

Parsons ES Response: *The datum used for the survey data in Table 2.2 is the National Geodetic Vertical Datum (NGVD) of 1929. The table will be amended to indicate this.*

Comment 5) Page 3-3, 2d paragraph, 2d sentence change wording to "The average annual precipitation".

Parsons ES Response: *The text will be changed as indicated.*

Comment 6) Page 4-16, various editorial items on this page, first full sentence, add "above" after detected, and state the actual MCL value. 2d paragraph, 3d sentence, delete one of the words "also". Last paragraph, 1st sentence, change word on to of, "vertical extent of".

Parsons ES Response: *The text will be changed to indicate benzene was detected below its Federal maximum contaminant level (MCL) of 5 micrograms per liter. The other editorial changes will be made as requested.*

Comment 7) Page 4-33, bottom of page, add space in 2d from last sentence "may be".

Parsons ES Response: *The text will be changed as requested.*

Comment 8) Sections 6 and 7, discussion of LTM, add some discussion on groundwater flow velocity and frequency of sampling, i.e. slower flow results in longer time between sampling events.

Parsons ES Response: *The following text will be added to Section 7.4, Sampling Frequency: "Groundwater advective velocity at the site ranges from 1.1 to 163 ft/yr, and averages 6.9 ft/yr (Table 3.1). The distance between monitoring well pair PES-6S,D at the downgradient edge of the TCE plume and downgradient well cluster 199 is approximately 450 feet (Figure 4.6). Therefore, an annual to biennial sampling frequency should be adequate to ensure that significant contaminant migration beyond well cluster 199 will not occur between sampling events, despite the fact that some dissolved contaminants will migrate faster than the advective groundwater velocity due to the effects of dispersion."*

B. Responses to AFCEE/ERT Comments dated 03 September 1999:

Comment 1) Page ES-2, Para 3, Sent 2: A source weathering rate of 7.3 percent per year is relatively high. Recommend giving brief rationale for this weathering rate.

Parsons ES Response: *As discussed in Section 5.4.4.1, Parsons ES experience with the AFCEE Natural Attenuation Initiative suggests that residual non-aqueous phase liquids (NAPL) may weather at rates as rapid as 10 percent per year. Initial source weathering rates were varied from 0 to 10 percent, with the 7.3% weathering rate determined by a "best-fit" during model calibration. The availability of measured concentration distributions at two different times (1993 and 1999) allowed for evaluation of various weathering rates. It was found that the 7.3% rate yielded simulation results most consistent with the data.*

Comment 2) Page v, Table of Contents: Recommend listing the appendices.

Parsons ES Response: *A list of appendices will be added to the table of contents.*

Comment 3) Page viii: The acronym for hollow-stem auger should be "HSA."

Parsons ES Response: *The acronym will be changed as indicated.*

Comment 4) Page 1-6, Sec 1.2, Para 1, Last Line: Suggest changing "midwestern" to "Midwestern."

Parsons ES Response: *The text will be changed as indicated.*

Comment 5) Page 2-8, Sec 2.1.2.3.2, Sent 3: To enhance clarity, suggest expanding as follows: ". . . around the well casing sequentially from the bottom upward with 20-40 . . ."

Parsons ES Response: *The text will be expanded as indicated.*

Comment 6) Page 2-13, Table 2.4: Recommend reporting northing and easting values to one decimal place to be consistent with stated accuracy of horizontal surveyed locations in Sec 2.5.

Parsons ES Response: *Northing and easting coordinates were reported to three decimal places by the surveyor (Appendix B). However, the horizontal accuracy specified for this project is one decimal place as stated in Section 2.5. To better reflect the accuracy and reliability of the horizontal coordinates, horizontal survey data in Table 2.4 will be rounded to one decimal place.*

Comment 7) Pages 4-14 and 4-15, Sec 4.2.1, Para 1, Last Sent: Suggest inserting "in" after "provided."

Parsons ES Response: *The text will be changed as indicated.*

Comment 8) Pages 4-15 and 4-16, Sec 4.2.1, Para 3, Sent 3: Recommend inserting "below" following "detected."

Parsons ES Response: *The text will be changed as indicated (actual revision is in Section 4.2.1, Paragraph 4, Sentence 3).*

Comment 9) Page 4-40, Table 4.10: Suggest expanding the label for the y-axis to include "Molar Ratio."

Parsons ES Response: *The y-axis label will be expanded as indicated.*

Comment 10) Pages 4-39 and 4-41, Sec 4.3.2, Para 2, Last Sent: To clarify the intended meaning, recommend revising as follows: ". . . TCE biodegradation via reductive dehalogenation is assumed . . ."

Parsons ES Response: *The text will be changed as indicated.*

Comment 11) Page 4-41, Sec 4.3.3, Para 2:

a. Line 4: To better reflect analytical/statistical certainty and reliability, suggest reporting the average chloride value to three significant figures (21.4 mg/L).

Parsons ES Response: *The average chloride value will be reported to three significant figures as indicated.*

b. Sent 4: To facilitate the reader's understanding and verification of this statement, recommend adding the TCE plume's 1-ug/L boundary on Figure 4.11. Additionally, suggest stating here or in another sentence the range and average of in-plume chloride values.

Parsons ES Response: *To clarify the distribution of chloride at the site, Parsons ES prefers to contour chloride concentrations in Figure 4.11, and to allow the reader to compare chloride distribution in Figure 4.11 to contaminant distributions in Figures 4.6 (TCE) and 4.7 (cis-1,2-DCE). The chloride distribution indicates that not only are chloride concentrations elevated within the contaminant plumes, but also downgradient of the plumes in a southeasterly direction (wells 201 and 236). This may be a result of the conservative nature of chloride (non-degraded and unretarded relative to TCE and cis-1,2-DCE) that causes a "shadow" effect downgradient from the contaminant plumes.*

This interpretation will be added to the text in addition to the range and average of chloride concentrations within the TCE plume as follows: "Chloride concentrations within the TCE plume (as defined by the 1 µg/L TCE contour) range from 13.7 mg/L at well PES-4D to 198 mg/L at well 203, and average 71 mg/L. Chloride concentrations also appear to be elevated downgradient from (southeast of) the CAH plume (wells 201 and 236). This may be a result of the conservative nature of chloride (non-degraded and unretarded relative to TCE and cis-1,2-DCE) that causes a "shadow" effect downgradient from the contaminant plumes"

Comment 12) Page 4-43, Sec 4.3.4, Para 2, Line 3: To better reflect analytical accuracy and certainty, suggest reporting the average chloride value to three significant figures.

Parsons ES Response: *There are no references to average chloride values in Section 4.3.4. However, oxidation/reduction potentials will be reported to three significant figures in this section.*

Comment 13) Page 4-49, 4.3.6.2, Para 1: The large range in nitrate-nitrogen suggests one or more anthropogenic sources such as fertilizer. Recommend the text briefly address potential sources of nitrate-nitrogen in the vicinity of LF-03. Additionally, because measured nitrate-nitrogen values reach 19.5 mg/L, suggest stating that concentrations greater than 10 mg/L exceed the Federal MCL for nitrate-nitrogen.

Parsons ES Response: *Parsons ES can find no reference to potential anthropogenic source of nitrate+nitrite (as nitrogen) at the site. As a vacant, grassy area, the site is not fertilized. However, the text will be amended to indicate that nitrogen concentrations in excess of 10 mg/L exceed the USEPA Federal drinking water MCL of 10 mg/L. The text also will be amended to state that monitoring locations exceeding this standard (233, 208, PES-1S, 209, and 209M1) are located immediately downgradient of the landfill (except 233), indicating that the landfill may be a source of elevated nitrogen concentrations.*

Because nitrate may be used as an electron acceptor in the degradation of organic carbon under nitrate reducing conditions, nitrate may compete with chlorinated solvents for use as an electron acceptor. Therefore, elevated nitrate concentrations may inhibit reductive dechlorination of TCE and cis-1,2-DCE.

Comment 14) Page 4-62, Sec 4.4, Para 3, Sent 2: To better reflect accuracy and certainty of these calculated biodegradation rates, suggest reporting them to no more than three significant figures.

Parsons ES Response: *Biodegradation rates will be reported to three significant figures throughout the text as indicated.*

Comment 15) Page 4-64, Sec 4.4, Line 6: To better reflect accuracy and certainty of these calculated biodegradation rates, suggest reporting them to no more than three significant figures.

Parsons ES Response: *Biodegradation rates will be reported to three significant figures throughout the text as indicated.*

Comment 16) Page 4-65, Sec 4.5, Para 1, Line 2: To better reflect accuracy and certainty of these calculated biodegradation rates, suggest reporting them to no more than three significant figures.

Parsons ES Response: *Biodegradation rates will be reported to three significant figures throughout the text as indicated.*

Comment 17) Page 5-16, Sec 5.5.1:

a. Para 1, Last Sent: Appendix E contains no list of calibration target wells as stated here. Recommend adding a table to Appendix E that enumerates the measured head, the simulated head, and the residual head value for each of the 43 target wells.

Parsons ES Response: *A list of calibration target wells with measured and simulated heads will be added to Appendix E.*

b. Para 2: Because the hydraulic conductivity (K) distribution for the three layers sounds complex, recommend adding maps of calibrated K values for the three model layers.

Parsons ES Response: *Maps of the calibrated K values for each of the three layers will be added to Appendix E.*

Comment 18) Page 5-23, Sec 5.5.2.4, Para 1: Suggest defining K_D as "distribution coefficient" as is done in the second paragraph of Section 5.5.2.4 and on page 5-19, Section 5.5.2.

Parsons ES Response: *K_D will be defined as the distribution coefficient as indicated.*

Comment 19) Page 6-6, Sec 6.2.3.1, Para 1, Last Sent: Groundwater velocity ranges over two orders of magnitude, not one as stated here.

Parsons ES Response: *The sentence will be changed to indicate that groundwater velocity ranges over two orders of magnitude.*

Comment 20) Page 6-23, Table 6.3: Suggest rounding itemized cost estimates to four significant figures (e.g., $194,400), to properly reflect accuracy/reliability of these estimates.

Parsons ES Response: *The itemized cost estimates will be rounded to four significant figures as indicated.*

Comment 21) Page 7-2, 7.2, Para 1: Thirty-one LTM wells seems excessive. Recommend consideration be given to deleting wells 198 and 241. Computer simulation reveals that these wells will remain outside the plume. Additionally, given the relatively slow groundwater velocity, suggest that downgradient wells 199 and 232 and side-gradient wells 236 and 238 not be sampled during the first two annual sampling events.

Parsons ES Response: *Wells 198 and 241 will be deleted from the recommended LTM plan. As noted in the text, the LTM plan should be reviewed periodically to determine if additional monitoring wells should be removed from monitoring. TCE has been historically (prior to 1999) detected at well 199 (Table 4.1), and also was detected at well 238 in 1999 (Table 4.4). Therefore, these wells should be sampled for each LTM event.*

While TCE has not been detected at wells 232 and 236, these wells are located within 200 feet downgradient of the 1993 TCE plume front as contoured on Figure 4.3. Given potential advective groundwater velocities at the site as high as 163 ft/yr (Table 3.1) and the effects of dispersion, Parsons ES believes it is prudent to include these wells in the first two annual LTM events. Again, the LTM plan should be reviewed periodically to determine if additional monitoring wells should be removed from monitoring based on observed plume behavior.

Comment 22) Page 7-1, Table 7.2:

a. If several proposed LTM wells are not sampled, the first two line items should be revised downward.

Parsons ES Response: *The first two line items in Table 7.1 will be revised downward in accordance with the response to Comment 21.*

b. The footnote references well installation; however, no new LTM wells are proposed. This apparent inconsistency should be resolved.

Parsons ES Response: *The reference to well installation in the footnote for Table 7.2 will be deleted.*

C. Response to F.E. Warren AFB Comment dated 13 October 1999:

Comment 1) F.E. Warren AFB requests an evaluation of total source reduction (i.e., landfill excavation).

Parsons ES Response: *The numerical model was run with all source terms removed as of 1999 to simulate a total source removal scenario. Model predictions at 10, 20, and 30 years are plotted on the attached Figure R-1. Comparison of this simulation to Alternative 1 (no source reduction, Figure 6.1) and Alternative 2 (50 percent reduction per year for two years, Figure 6.2) indicates that total source reduction has minimal impact on the downgradient migration or persistence of the TCE plume.*

The primary benefit of total source reduction is to remove uncertainty and any future risk associated with a lack of characterization of the TCE source. A secondary benefit is to reduce TCE concentrations and persistence immediately downgradient of the plume source area. However, for all three scenarios, concentrations of TCE in the downgradient portion of the TCE plume are expected to attenuate at a similar rate to approximately 10 µg/L in 30 years. This is because the center of mass of the TCE plume has already detached from the source area. The highest TCE concentration in 1993 was 118 µg/L at sampling location HP18 (replaced by sampling location PES-1S in 1999), while in 1999 the highest TCE concentration was 93.1 µg/L at sampling location 209, located approximately 190 feet downgradient of sampling locations HP18 and PES-1S. This suggests that the plume "hotspot" has migrated approximately 190 feet in the 6 years between the 1993 and 1999 sampling events.

Parsons ES will include the total source reduction scenario in the final TS report if requested by F.E. Warren AFB.

If you have any questions or comments regarding these responses, or require additional information, please call me at (303) 831-8100.

Sincerely,

PARSONS ENGINEERING SCIENCE, INC.

Bruce M. Henry, P.G.
Project Manager

cc: Brady Baker – F.E. Warren AFB

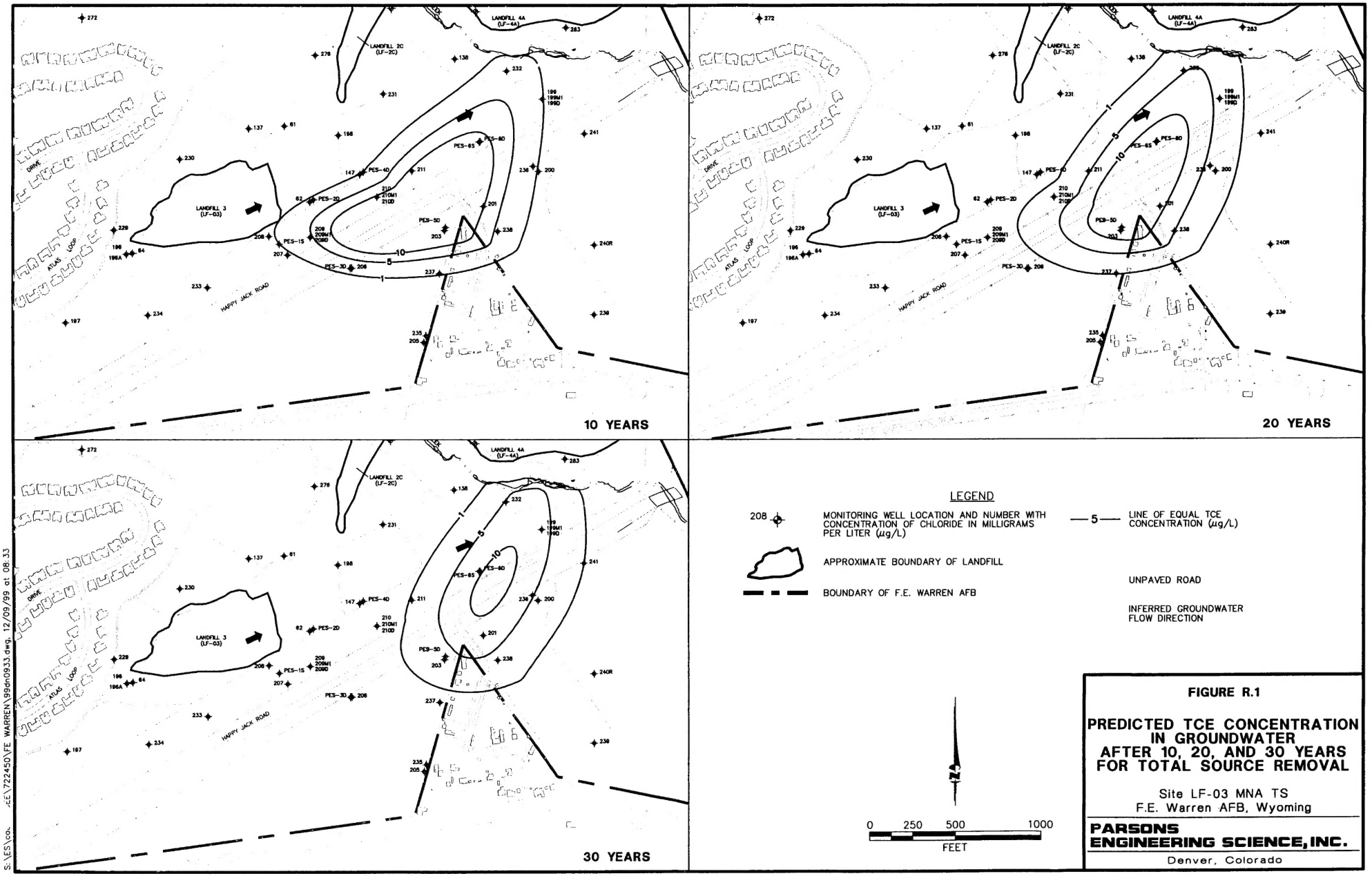

FIGURE R.1

PREDICTED TCE CONCENTRATION IN GROUNDWATER AFTER 10, 20, AND 30 YEARS FOR TOTAL SOURCE REMOVAL

Site LF-03 MNA TS
F.E. Warren AFB, Wyoming

PARSONS ENGINEERING SCIENCE, INC.
Denver, Colorado

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